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Development of a Gait Score for the Assessment of End-stage Ankle Osteoarthrosis and Outcome of Related Surgery

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Development of a Gait Score for the Assessment of End-stage Ankle Osteoarthrosis and Outcome of Related Surgery

Thèse de doctorat ès sciences de la vie (PhD)

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Prof. Francis Verdun

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Résumé

Aujourd'hui, en pratique clinique, l'évaluation fonctionnelle des patients souffrant de pathologies du pied et de la cheville se limite principalement à une approche subjective qui se base sur des questionnaires cliniques. Ceci est dû au fait que la plupart des analyses objectives de référence ne peuvent être conduites que dans des laboratoires de recherche en raison de la taille et du coût des équipements. Néanmoins, grâce au développement récent d'un système ambulatoire d'analyse de la marche qui se compose de capteurs inertiels 3D et de capteurs de pression embarqués, l'incorporation de l'analyse de la marche dans la pratique clinique est maintenant possible.

Le but de cette thèse est de montrer la capacité de ce système portable à étudier une pathologie spécifique du pied et de la cheville et présente un score d'évaluation quantitatif basé sur l'analyse de la marche.

L'arthrose de cheville terminale (AOA) a été sélectionnée car c'est une pathologie progressive et invalidante dont les traitements dépendent de la sévérité. Les chirurgies les plus fréquemment appliquées sont l'arthrodèse de cheville (AA), l'arthroplastie totale de cheville (TAR) et, dans des cas trop sévères ou des situations d'échec, l'arthrodèse calcanéo-talo-tibiale (TTCA). En général l'évaluation subjective montre que les résultats sont, somme toute, assez semblables quelle que soit la technique chirurgicale appliquée. Néanmoins, l'analyse objective de la marche montre que des différences significatives peuvent être observées et ce, pas seulement pour le pied malade ou opéré, mais aussi pour le pied opposé.

Le travail de thèse se base sur l'étude de 89 participants dont des sujets contrôles, des patients souffrant d'arthrose de cheville terminale, des patients après arthrodèse de cheville, prothèse de

cheville et arthrodèse TTCA. Les participants ont été évalués fonctionnellement en se basant sur des scores cliniques (AOFAS, FAAM et EQ-5D) ainsi que par analyse ambulatoire de la marche. Les analyses de marche ont été réalisées dans un espace ouvert permettant aux participants de marcher naturellement. Pour chaque participant on a examiné le côté affecté et le côté sain.

Dans le but de rendre le système d'analyse de la marche assez simple pour être utilisable en pratique cette thèse s'est basée sur l'analyse des composantes principales pour identifier les paramètres pertinents pour la clinique tout en maintenant l'information importante. Un modèle de marche prédictif a pu ensuite être développé qui puisse être utilisé comme un score pour analyser les patients et identifier des information qui ne sont pas détectables par l'analyse subjective habituelle.

La réduction du nombre de paramètres pertinents de 48 à 17 a montré sa cohérence avec le maintien d'une corrélation forte (>0.7) entre tous les groupes et le set complet de paramètres. Des scores paramétriques individuels ont ensuite pu être attribués et un score total a pu être calculé. Les scores finaux, qui montrent notamment la supériorité fonctionnelle de l'arthroplastie totale de cheville, suivie de la TTCA et de l'AA, s'alignent avec les résultats connus d'analyse de marche.

Ce travail de thèse est un pas important en direction d'une plus large utilisation de l'analyse de marche ambulatoire en pratique clinique. En effet, un système ambulatoire d'analyse de marche a été appliqué avec succès puis a servi au développement d'un score de marche à la fois précis et simplifié qui offre le potentiel d'utiliser l'analyse de la marche beaucoup plus facilement en pratique clinique et en recherche.

Summary

Today's clinical practice for determining the functional status of patients presenting with foot and ankle pathologies and to assess the efficacy of their surgical treatment is mainly restricted to subjective functional assessment based on questionnaires. This is due to the current gold standard for objective assessment being restricted to research laboratories as a result of the size and cost of the equipment. However, with the recent development of a cost effective, portable, ambulatory gait analysis (AGA) system, which uses wearable 3-D inertial sensors and pressure insoles, the incorporation of an objective gait assessment as part of clinical practice is now a possibility.

The goal of the present thesis is to show the capability of such a system in reference to a selected foot and ankle pathology, and to introduce a quantitative functional gait based outcome score.

The selected pathology was end-stage ankle osteoarthrosis (AOA) because it is a progressive debilitating disease which can be addressed by various surgical treatments, depending on its severity. The most common treatments include ankle arthrodesis (AA) and total ankle replacement (TAR) and, failing that, tibiotalocalcaneal arthrodesis (TTCA). In general, subjective assessment finds the outcome of all surgeries to be fairly similar. However, objective gait assessment found that significant differences are to be seen, not only in a patients affected / operated side, but also the contra lateral unaffected / un-operated side.

The present work enrolled 89 participants, including healthy controls, end-stage AOA patients, AA patients, TAR patients and TTCA patients. The participants were examined using a functional assessment based on clinical scores (AOFAS, FAAM and EQ-5D) as well as an ambulatory gait

analysis system. Trials were performed in an open space to allow participants to walk naturally. Both sides, for each participant, were tested.

To simplify objective assessment for clinical practice, it was the aim to utilize the ambulatory system to establish clinically relevant gait parameters and to subsequently develop a predictive gait model which can be used as a score in assessing patients and identifying information missed by current subjective assessments. For the development of a simple, yet meaningful gait score for AOA and its surgical corrections, robust parameter reduction using principal component analysis was carried out to minimize the number of relevant parameters, whilst maintaining the majority of important information.

The resultant reduction to 17 out of 48 parameter set was consistent in showing strong correlation with the full parameter set across all groups (>0.7). Individual parameter scores were then given to each parameter based on an established outlier classification and a total gait score was calculated accordingly. Final scores align with all previous gait analyses with TAR patients receiving the highest scores, followed by TTCA, and AA each showing improvement over AOA patients.

The work presented here is an important step towards promoting the use of ambulatory gait analysis in clinical practice. Hence, a validated AGA system was successfully applied and developed to a simplified and accurate gait score which offers the potential to use AGA more easily in clinical practice and for research purposes.

List of acronyms

AA	Ankle arthrodesis
ADL	Activity of daily living
Aff	Affected side in ankle osteoarthrosis
AGA	Ambulatory gait assessment
AOA	End-stage ankle osteoarthrosis
AOFAS	American orthopedic foot and ankle score
BW%	Percentage of body weight
CRP	Continuous relative phase
CV%	Coefficient of variance in percentage
DMAA	Distal metatarsal articular angle
EQ-5D	Euroquol 5 dimensional score
FAAM	Foot and ankle ability measure score
F&A	Foot and ankle joint
FC	Forefoot central
FL	Forefoot lateral
FM	Forefoot medial
GCT%	Percentage of gait cycle time
HF-FF	Hindfoot-forefoot intersegment
HL	Hindfoot lateral
HM	Hindfoot medial
HSP	Heel-strike pitch angle
HVA	Hallux valgus angle
HV	Hallux valgus
IMU	Inertial measurement unit
IQR	Inter quartile range
Max F	Maximum force
Max P	Maximum pressure
ML	Midfoot lateral
MM	Midfoot medial
M1/M2	Intermetatarsal angle between first and second metatarsal
MTP1	First metatarsophalangeal joint
OA	Osteoarthrosis
Op	Operated side
PAVS	Peak angular velocity of shank
PCA	Principal component analysis
PC	Principal component
PP	Plantar pressure

PROM	Patient reported outcome measure
PSS	Peak swing speed
Q	Quartile
QOL	Quality of life
r	Pearson's correlation coefficient
ROM	Range of motion
SH-HF	Shank-hindfoot intersegment
SH-FF	Shank-forefoot intersegment
STP	Spatiotemporal parameters
St%	Percentage of stance phase
T^2	Hotelling's T-squared statistic
TAR	Total Ankle Replacement
Tc	Total contact duration
Tin	Initial contact duration
Tout	Terminal contact duration
TF	First toe
TOP	Toe-off pitch angle
TS	Second toe
TT	Third to fifth (lateral) toes
TTCA	Tibiotalocalcaneal Arthrodesis
Unaff	Unaffected side in ankle osteoarthrosis
Unop	Unoperated side

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1 Introduction

1.1 Ankle joint

The foot and ankle (F&A) is arguably one of the most complex skeletal architecture and functional unit in the human body, including 28 bones and more than 30 joints. The ankle complex is, in fact, a multi-joint mechanism made up of the true ankle (tibiotalar) joint and the subtalar (talocalcaneal) joint (Figure 1), and plays an important role in locomotion [Leardini et al., 2014]. A true ankle joint is a hinge type of joint, made by the distal end of the tibia and fibula and the proximal side of the talus. The three articular surfaces include:

1. Medially, the articulation between the medial malleolus and the medial border of the talus.
2. Laterally, the articulation between the lateral malleolus the lateral border of the talus.
3. Centrally, the articulation between the distal tibia and the superior dome of the talus.

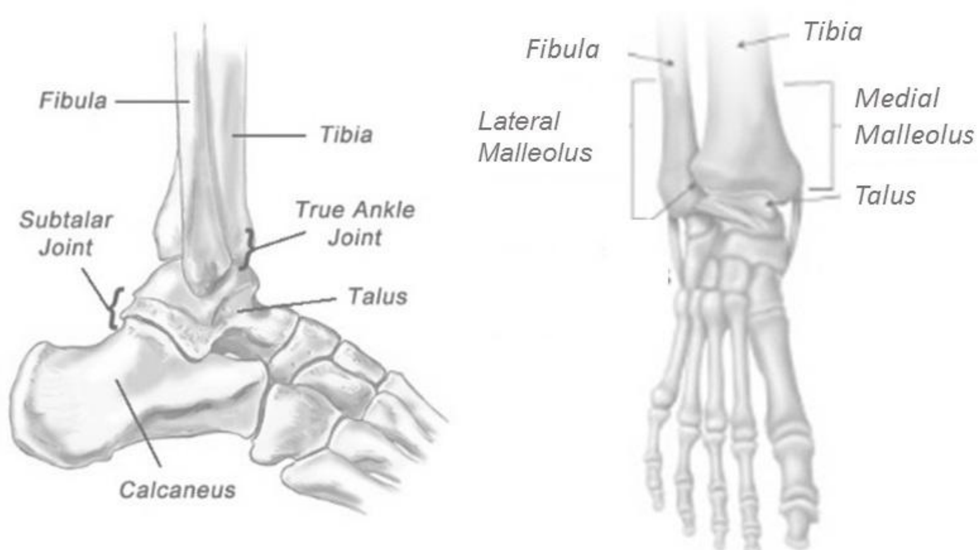

Figure 1: The Ankle Joint Complex, presenting tibiotalar articulation (true ankle joint) and talocalcaneal articulation (subtalar joint), lateral view (left), anterior view (right).*(Figure is adopted from the Lotus Physiotherapy and Rehabilitation: http://www.loftusphysiorehab.com.au), and from the American Academy of Orthopedic Surgeons: http://orthoinfo.aaos.org)*

The articular cartilage covers the articulating surfaces of the joint. The articular cartilage of the ankle joint, unlike that of other weight bearing joints, is thin and uniform in thickness, which helps distribute stress under loaded situation [Shepherd and Seedhom, 1999, Simon et al., 1973, Wynarsky and Greenwald, 1983]. This is one of the reasons why primary osteoarthrosis is not common in the ankle joint.

The normal freedom of motion around the ankle joint is 20 degrees of extension (also known as dorsiflexion) and 50 degrees of plantar flexion in the sagittal plane, 3 degrees of eversion and 8 degrees of inversion in the coronal plane, while motion in the transverse plane is almost neglectable. A normal loading force during level ground walking is 3-5 times the body weight and tends to increase with more demanding activities such as running or jumping [Stauffer et al., 1977]. Moreover, compared to other weight bearing joints, F&A joints are generally subjected to a higher force per square centimeter [Thomas et al., 2006].

1.2 Ankle degenerative diseases

The type of arthritis causing low inflammatory chronic progressive degeneration of the joints is osteoarthritis. The term was used interchangeably with osteoarthrosis, but recently the definition for osteoarthrosis in medical literature has been redefined as a non-inflammatory chronic progressive degenerative disease of the joints [Berenbaum, 2013, Mercuri, 2008]. Both osteoarthritis and osteoarthrosis are associated with wear and tear of the intra-articular cartilage, which eventually leads to narrowing of the joint space, enhanced subchondral bone sclerosis, formation of osteophytes, and development of subchondral cysts (Figure 2). Symptoms include pain, swelling, joint contracture, and muscle atrophy directing towards different levels of functional limitation [Buckwalter et al., 2004, Lawrence et al., 1998]. In 70-80% of cases ankle arthritis is post-traumatic and non-inflammatory in origin [Thomas et al., 2006, Valderrabano et al., 2009]. In 10-15% of cases, ankle arthritis develops secondary to other diseases, for example rheumatoid arthritis, [Michelson et al., 1994]. While <10% of cases reported are of primary origin [Thomas et al., 2006, Valderrabano et al., 2009].

Figure 2: Radiographic image of end-stage ankle osteoarthrosis, lateral (left) and antero-posterior (right) views. Reduction of joint space, subchondral bone sclerosis and osteophytes can be observed.

In Europe and North America, 15-20% of the adult population suffers from arthritis with ~10% of those including osteoarthrosis [Lawrence et al., 1998, Saltzman et al., 2005, Glazebrook et al., 2008]. In fact, it has been projected that 25% of the American adult population (67 million people) would be diagnosed with some form of arthritis by 2030 [Hootman and Helmick, 2006]. Nonetheless, the incidence is low for ankle joint, compared to hip and knee joints, however the debilitating effect of the disease is comparable in terms of pain and loss of function negatively affecting patients' quality of life (QOL) [Thomas et al., 2006, Agel et al., 2005]. The severity of the disease is classified based on standardized ankle radiographs. Its functional implication can be assessed using various clinical scores. Different treatment options are available including medication, physiotherapy, footwear, lifestyle modification, as well as various surgical corrections.

1.3 Surgical corrections for end-stage ankle osteoarthrosis

Several surgical options are available to treat ankle osteoarthrosis (AOA), ranging from joint preserving surgeries to salvage procedures [Crevoisier, 2009]. However, choosing the optimal surgical solution relies on multiple intrinsic and extrinsic factors including: severity of degeneration, number of joints involved, quality of the bone and of the surrounding soft tissues, general health of the patient, age of the patient, life style of the patient and, importantly, expectations of the patient from the surgery. The following subsections detail the common surgical options for AOA.

1.3.1 Ankle arthrodesis

Ankle arthrodesis (AA) or tibiotalar fusion was first introduced in 1879 [Albert, 1879] and has since become the most commonly used surgical treatment for end stage AOA. For a long time it has been widely regarded as the gold standard (Figure 3). AA has shown a positive outcome in terms of pain relief and functional improvement (based on clinical scores) [Daniels et al., 2014, Esparragoza et al., 2011, Haddad et al., 2007]. However, in terms of mobility, the tibiotalar joint is completely fused which, in turn, reduces the foot mobility by ~70% in the sagittal plane [Abdo and Wasilewski, 1992]. The residual mobility is obtained utilizing compensatory motion of the subtalar and mid tarsal joints. The tibiotalar joint should be fused in a neutral dorsiflexed position with ~5 degrees of hindfoot valgus and 5 to 10 degrees of external rotation [Buck et al., 1987, Abdo and Wasilewski, 1992, Bertrand et al., 2001]. Studies suggest that an optimal fusion position, along with a good subtalar joint health, results in better functional outcome [Bertrand et al., 2001, Ben Amor et al., 1999].

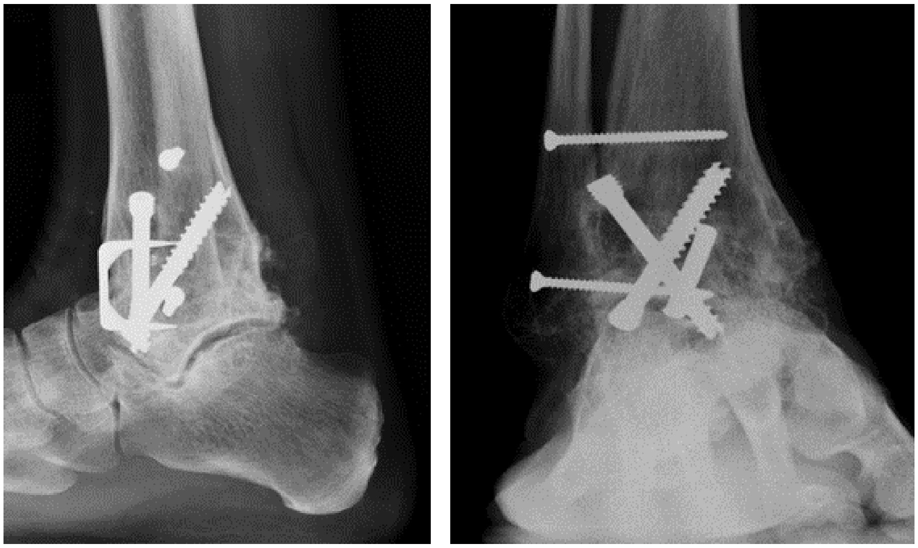

Figure 3: Anteroposterior (right) and lateral (left) radiographic images presenting a consolidated ankle arthrodesis. To achieve fusion primary stabilization has been performed using internal screws and staple fixation.

1.3.2 Total ankle replacement

Total ankle replacement (TAR) was first performed in 1970 [Henne and Anderson, 2002]. Since then several changes have been made in the prosthesis designs [Henne and Anderson, 2002, Saltzman, 2000, Neufeld and Lee, 2000] to reduce the rate of implant failures and improve implant longevity (Figure 4). Current TAR designs include both fixed and mobile bearing systems. The new generation of implants also have superior anatomic designs which can reproduce close to natural joint kinematics [Rush and Todd, 2013]. Midterm clinical results are comparable to those obtained after AA [Haddad et al., 2007]. However, the implant longevity is still compromised as it deteriorates with time [Henricson and Carlsson, 2015, Jastifer and Coughlin, 2015]. Note that this is also as a result of higher physical activity level in TAR patients

[Schuh et al., 2012, Valderrabano et al., 2006, Naal et al., 2009], but this tends to also be a sign of superior functionality. As such, TAR is generally preferred for older patients with low physical demand. Nonetheless, younger patients today opt for surgery not just for pain reduction but to improve functionality and, according to the American College of Foot and Ankle Surgeons, the demand for TAR surgeries among younger patients has constantly been on the rising [ACFAS, 2012].

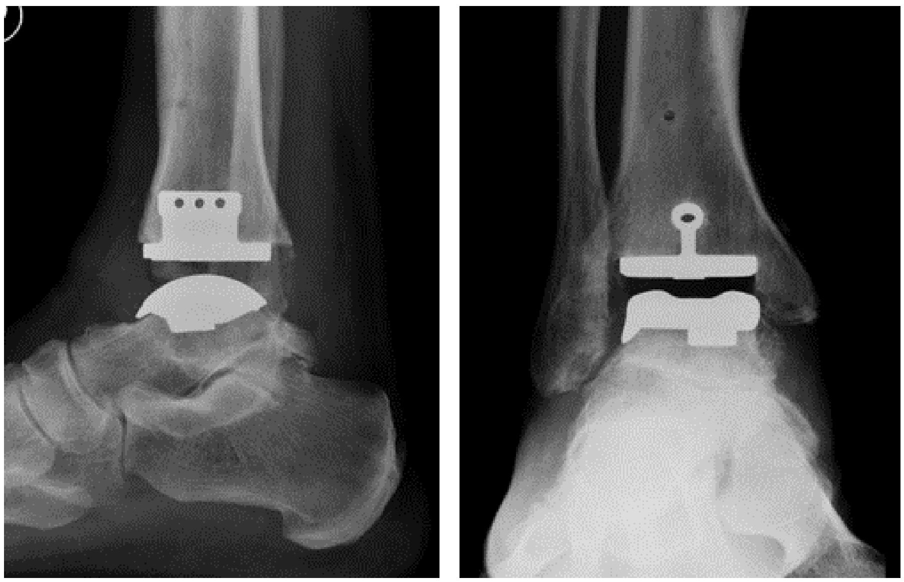

Figure 4: Anteroposterior (right) and (left) lateral radiographic views presenting a total ankle replacement using a Salto Talaris® fixed bearing anatomical prosthesis.

1.3.3 Tibiotalocalcaneal arthrodesis

Tibiotalocalcaneal arthrodesis (TTCA), involves the fusion of both the tibiotalar and the subtalar joints (Figure 5). It was first introduced by Russotti and Johnson in 1988 for the treatment of combined OA of the tibiotalar and subtalar joints [Russotti et al., 1988]. TTCA is, however, not a frequently used procedure and is usually used as a salvage procedure following the failure of other ankle and hindfoot surgeries or as primary procedure for complex ankle-hindfoot pathologies [Chou et al., 2000]. Use of a retrograde intramedullary nail is the modern approach as it has the advantage of providing better primary stability compared to other implants. Recent studies have shown good clinical results and high patients' satisfaction using this technique[Thomas et al., 2015].In terms of function, Gellmann et al reported a similar restriction in the sagittal plane motion for both AA and TTCA, however, in the frontal plane, there is a 40% decrease in motion for TTCA patients [Gellman et al., 1987].

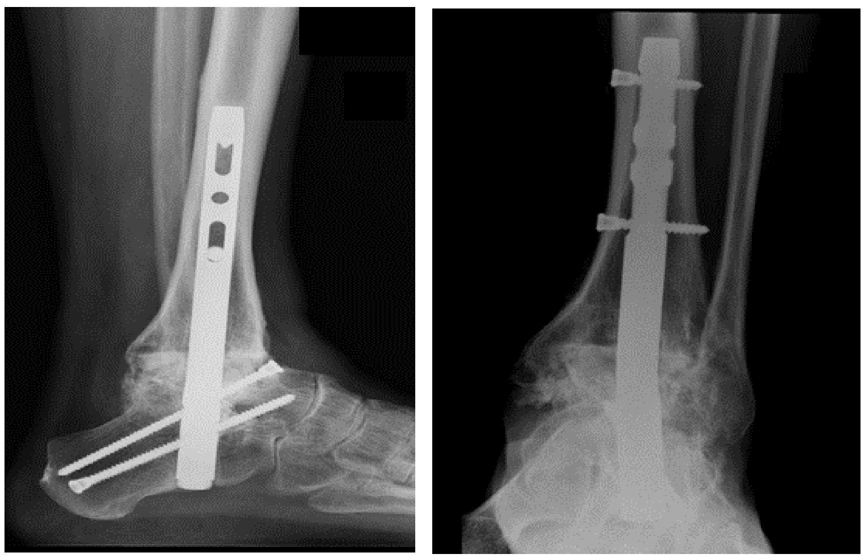

Figure 5: Anteroposterior (right) and lateral (left) radiographic image presenting a tibiotalocalcaneal fusion using a retrograde intramedullary locking nail.

1.4 Outcome assessment in ankle surgeries

Outcome assessment of orthopedic surgeries play an important role in health care delivery as it help surgeons measure the efficiency of the surgery [Ayers and Bozic, 2013]. Previously, the outcome of orthopedic surgeries was determined solely from the surgeons' perspective (radiographic results, physical examination) [Lieberman et al., 1996]. However, in last few decades patient perspective has been given higher importance [Bayley et al., 1995, O'Connor and Brinker, 2013]. As a result there has been a continuous rise in the popularity of subjective assessment surrounding patient reported outcome measures (PROMs) [Franklin et al., 2013, Pinsker et al., 2013]. In general, the absence of quantitative and qualitative assessment of gait biomechanics is the biggest setback in today's clinical setting.

1.4.1 Radiographic assessment

At present, both pre and post-operative outcome assessment of end-stage ankle surgeries is mainly based on radiographic results [Saltzman et al., 2010, Ellington et al., 2013, Bestic et al., 2008]. Pre-operative radiographic assessment looks at the joint in a static loaded position and assists in classifying the severity of AOA. Post-operatively, radiographic results assess the success of the operation based on the anatomic structures. For example, good alignment and union following AA and TTCA, or good bone and implant health, along with the good implant position, in TAR. Radiographic results also assess internal complications including nonunion, fractures, adjacent joint arthritis, perihardware lucency or fracture, syndesmotic screw loosening, hardware fracture, heterotopic ossification and or increased varus or valgus position of the ankle [Lee et al., 2013, Houdek et al., 2014]. Overall, radiographic assessment is an important anatomical assessment method which helps in treatment decision making and in assessing the success of the operation. However, radiographic assessment can only view the joint in a static loading position and as such does not take into consideration dynamic loading, which is important for functional independence and to provide a complete picture in terms of joint functionality.

1.4.2 Subjective outcome assessment

Assessment of the functional status of patient post-operatively, generally relies on subjective questionnaires consisting of PROMs, along with the clinician reported scores [Nunley et al., 2012, Ellington et al., 2013, Saltzman et al., 2010]. Today, a variety of scores are used in clinical practice, including global health status scores, region specific scores, and disease specific scores [Picavet and Hoeymans, 2004, Martin et al., 2005, Pinsker and Daniels, 2011, Roos et al., 2001, Domsic and Saltzman, 1998, Hiller et al., 2006]. There are, however, known issues with this subjective assessment approach and numerous studies have questioned the validity and precision of such methods, especially for the outcome of F&A surgeries [Pinsker et al., 2013, Pinsker and Daniels, 2011, Button and Pinney, 2004, Parker et al., 2003, Naal et al., 2010, Hunt and Hurwit, 2013, Mani et al., 2015]. In particular, PROMs have been shown to give ambiguous results as patients do not reliably estimate their functionality, i.e. pain thresholds, activity level, general apprehension, etc[O'Connor and Brinker, 2013, Bernstein, 2012]. Due to such an inherent flaw of subjectivity, it is, therefore, generally accepted that rating the outcome of a surgery purely based on PROMs is not justifiable [Noble et al., 2013]. As such, in a clinical setting, it would be more practical to use empirical evidence based assessment measures, i.e. objective [Martin and Irrgang, 2007]. However, due to being both time and cost effective, subjective scores are still widely used in clinical practice and research. In fact, more scores of this type are being introduced every few years [Manoli et al., 1997, Martin et al., 2005, Roos et al., 2001, Dawson et al., 2011, Angthong et al., 2011, Coster et al., 2012, Morssinkhof et al., 2013, Niki et al., 2013, Martinelli et al., 2014], while methods of objective evaluation of a patient's functional status following F&A surgeries are currently either inadequate or still require improvement to be used in clinical practice.

The only available objective test for physical therapists to assess functional status in rehabilitation setting includes "timed up and go test" and "6 minute walk test", however these tests are found to be somewhat simplistic and cannot fully describe the qualitative aspect of gait. Moreover, these are first and foremost fitness tests and where not originally designed for the assessment of activity of daily living (ADL) [Senden et al., 2011]. To add to this, a high non-compliance rate of patients in following the prescribed home-based exercise prescription[Jack et al., 2010], can result in physiotherapists being generally misinformed about a patient's functional status. Nonetheless, a standardized objective gait assessment method would solve this problem. Furthermore, the introduction of gait training, using real-time movement feedback, can be motivational for the patient as they are capable of seeing their progress and can, for example, establish personal goals [Kim and Mugisha, 2014].

1.4.3 Gait assessment

Gait assessment involves the study of locomotion. In 1890, Christian Wihhelm Braune and Otto Fischer first studied gait mechanics in humans[Baker, 2007]. However, with the naked eye, it was not possible to capture the details of the human gait. In early 1900, pioneers Eadweard Muybridge and Étienne-Jules Marey developed a motion capture system, which completely changed the study of gait assessment [Baker, 2007] and today, with modern advancements in motion capture, it is generally agreed to be the best method of assessing biomechanics. Gait assessment can provide information regarding balance, joint loading, and joint range of motion as well as spatial and temporal aspects of gait. Note that, despite the advantages in terms of clinical application, gait assessment is restricted generally to research laboratories due to the high cost and size of equipment required. However, with recent advancements in technology, gait assessment in a clinical setting is now very much a possibility.

Laboratory confined gait assessment

A gait lab consists of video and or infrared cameras and a pressure embedded walkway. For gait assessment, the retroreflective markers are placed on anatomical locations as they are tracked by the infrared cameras which give complete information of the movement of each joint in 3-D as well as measure the spatial, temporal and kinematic parameters of gait. While the force plates have flat, rigid array of pressure sensors embedded in the floor, walking ramp or treadmill. The size of force plates are usually between 2-10m long and can only measure 1 to 5 consecutive steps at any given time. This system has been found to be accurate and reliable for gait assessment and is currently the gold standard; however, measurement device errors, calibration problems, soft tissue artifacts and marker displacement are some of the commonly faced problems. Furthermore, patients' need to make contact with the center of the force plate with enough force to achieve an accurate reading [Razak et al., 2012]. This is one of the major drawbacks, as patients consciously place their feet on the force plate rather than adhering to their natural walking pattern. Moreover, a walking distance of 2-10 m in a safe lab environment is not functionally representative.

Ambulatory gait assessment

Ambulatory gait assessment (AGA) is a new method that is not restricted to a laboratory environment. It utilizes body worn 3-D motion sensors (Accelerometer and Gyroscope) and pressure sensor embedded insoles[Tao et al., 2012]. An inertial measurement unit (IMU) combines the use of 3-D accelerometers and gyroscopes, which are commonly available motion sensors. The accelerometer measures motion, the gyroscope measures angular velocity and the pressure insoles, which have sensors embedded in the shoe, measure the applied pressure at any given time. Unlike lab based method AGA is portable, affordable, and convenient. Moreover, it gives the freedom to perform a test anywhere, for any distance and therefore is able to capture the natural gait of a patient effectively.

2 Research questions

As mentioned above, three dimensional gait analysis is a superior assessment method compared to PROMs. However, gait assessment has always been regarded as an expensive, complex, time and space consuming method, hence, more applicable for research than clinical perspective. But with the advancement in technology, the AGA methods have been developed which are relatively less expensive, easy to use and less space consuming. However, the time consuming part in terms of handling the raw gait data and interpretation of an overwhelming number of gait parameters with respect to particular pathologies is still a challenge.

In terms of practicality, an assessment method to be used in clinical practice should be, reliable, robust, clinically meaningful and still easily applicable. Therefore, there is a need to simplify gait assessment by removing the redundant gait parameters and find the ideal number of clinically relevant parameters which could capture most alterations in patient's gait and can be easily managed in busy clinical setting.

2.1 Goals of the thesis

The research question of the thesis is answered based on 4 goals:

1. Identify clinically relevant gait parameters.
2. Quantify the importance of bilateral gait assessment.
3. Compare subjective and modern objective gait assessment methods.
4. Develop a robust objective gait score for use in clinical practice.

3 Methodology

3.1 Gait Assessment

3.1.1 Ambulatory gait assessment used in this research

The AGA system used throughout the present research included five 3-D inertial sensors, each consisting of 3-D gyroscopes and 3-D accelerometers as well as PEDAR® pressure insoles. The system has already been validated against the gold standard lab based method [Rouhani, 2010], see Figure 6.

Figure 6: Validation of utilized ambulatory gait assessment against the gold standard lab based method. Patient wearing inertial sensors and pressure insole, walking over the pressure plate embedded platform surrounded by high frame rate cameras. Image courtesy of H. Rouhani [Rouhani, 2010].

Sensor Placement

Inertial sensors were attached to the medial aspect of both tibia, as well as to the posterior aspect of the great tuberosity of the calcaneus, between the bases of the first and the second metatarsals, and on the dorsal aspect of the proximal phalanx of the first toe, of the foot being tested, see

Figure 7.All five sensors were connected to two portable data-loggers (Physilog®, BioAGM, CH).

Figure 7: Sensor placement for the ambulatory gait assessment system. On the tested ankle (left side) sensors are placed at the dorsal aspect of the proximal phalanx of the first toe, between the bases of the first and the second metatarsals, the great tuberosity of the calcaneus.

Pressure insoles

The insoles were available in 4 sizes, see Figure 8, and custom-made sandals were used to adequately secure the pressure insoles. The plantar pressure data were collected, from the 99 cells of the Pedar-X® insoles, at the sampling rate of 200 Hz. The stance time of the gait cycles for each trial was identified using sum of the pressure over loaded elements of the insole [Rouhani et al., 2011]

Figure 8: Different PEDAR insole sizes.

After the patient preparation, functional calibration of the system is performed by fast passive motions of the knee joint followed by walking 50m long straight hospital corridor. All participants subsequently perform two walking trials of 50m each at their natural walking speed. The protocol for the gait assessment can be seen in Appendix I. Raw data is then subject to post-processing algorithms including the splitting of Pedar data into 10 subregions of foot. These algorithms were written at the École Polytechnique Fédérale de Lausanne (EPFL),in Matlab® to allow for subsequent statistical analysis [Rouhani, 2010, Mariani, 2012].

3.1.2 Multisegment foot model

This study utilized multisegment foot model for joint kinematic and plantar pressure assessment (Figure 9). Multisegment foot models can differentiate between movements of each segment and are therefore significantly accurate. For kinematic assessment, study utilized the multisegment foot model dividing the foot into 4 segments including shank (SH), hindfoot (HF), forefoot (FF) and toes (TO) [Rouhani et al., 2012]. Furthermore, for plantar pressure assessment division of foot into multiple subregions helps to provide more localized assessment. Overall the foot is divided into 10 subregions, namely; Hindfoot lateral (HL), Hindfoot medial (HM), Midfoot lateral (ML), Midfoot medial (MM), Forefoot lateral (FL), Forefoot medial (FM), Forefoot central (FC), First toe (TF), Second toe (TS), Lateral toes (3rd to 5th) (TT) [Rouhani et al., 2011].

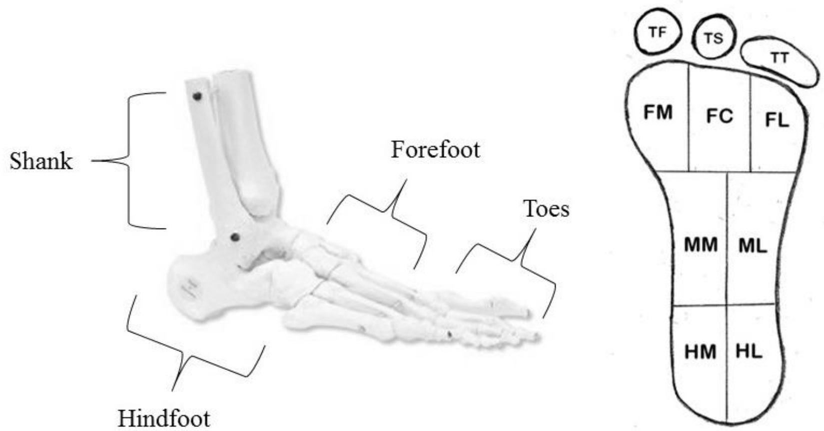

Figure 9: Segmentation of foot for kinematic assessment (left) as well as ten sub-regions of foot (right) for plantar pressure assessment.

3.1.3 Gait parameters assessed in the study

Spatiotemporal parameters

Stance Phase (% GCT): Walking is generally a cyclic event and the time which a foot spends in contact with the ground is defined as the stance phase. It starts with heel strike of a foot and continues until the toe of the same foot leaves the ground. It constitutes about 60% of the gait cycle time (GCT).

Swing Phase (%GCT): The time in which the foot is not in contact with the ground during the gait cycle is defined as the swing phase. It starts with toe-off phase and continues until just before the heel strike of the same foot. It constitutes about 40% of the GCT.

Cadence (steps/min) is defined as the number of steps per minute.

Stride length (m) is the distance between two successive placements of the same foot while walking or running. It also represents one gait cycle.

Peak swing speed (PSS) (°/sec) represents the peak angular velocity of the shank (PAVS) during the swing phase.

Inner stance phase events in St % include (see Figure 10):

Load, the initiation of the stance phase as the heel touches the ground. It constitutes to between 10-12% of the stance phase.

Foot flat is the second event of the stance phase when the whole foot is in contact with the ground. It constitutes to between 50-60% of the stance phase.

Push-off is the last event during the stance phase when only toes are in contact with the ground, just before the start of the swing phase. It constitutes to between 30-40% of the stance phase.

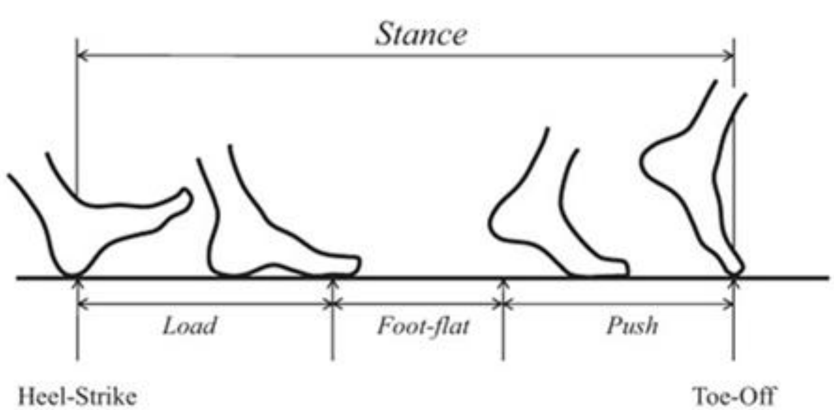

Figure 10: Inner stance events showing load, foot-flat and push-off phases along with the heel-strike (initial contact) and toe-off (terminal contact). Image courtesy of B. Mariani [Mariani et al., 2013].

Heel-strike pitch angle (HSP) (°) is the angle between the ground and the heel during the initial contact of the foot to the ground.

Toe-off pitch angle (TOP) (°) is the angle between the ground and the toes during the terminal contact of the foot to the ground.

Kinematic parameters:

Joint kinematics assesses the range of motion (ROM) during dynamic activity. Intersegment motion along the sagittal (dorsiflexion/ plantarflexion), coronal (inversion/ eversion) and transverse (internal rotation/ external rotation) planes (Figure 11) were assessed. Motion around four intersegments was assessed, including; forefoot-hindfoot (FF-HF), hindfoot-shank (HF-SH) forefoot-shank (FF-SH) and toe-forefoot (TO-FF) [Rouhani et al., 2012]. Furthermore, coordination between the segments performing the motion was assessed in the sagittal plane for three intersegments including- FF-HF, HF-SH and FF-SH, utilizing the continuous relative phase (CRP) method (detailed in section 5.3.3).

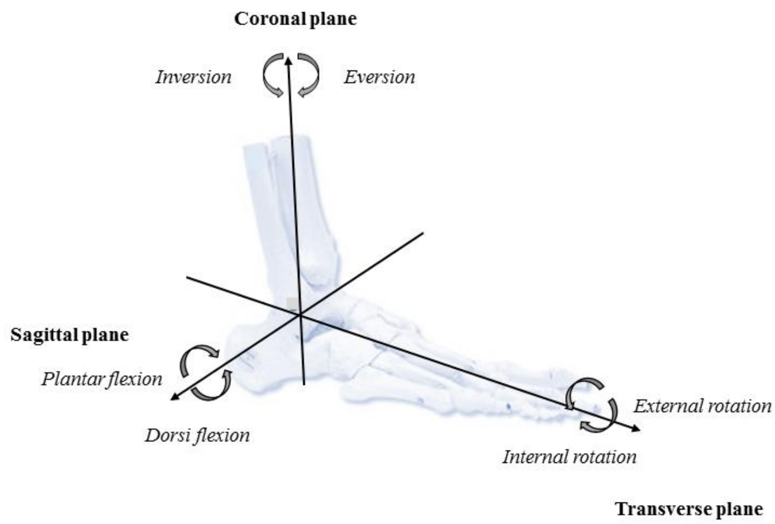

Figure 11: Ankle motion for each of the three planes; sagittal, coronal and transverse.

Plantar pressure parameters:

Initial Contact (Tin) (St% time) is the time of initial contact of each foot subregion to the ground.

Terminal Contact (Tout) (St% time) is the time of terminal contact of each foot subregion.

Total contact duration (Tc) (St% time) is the total time a foot subregion remains in contact to the ground, i.e. Tc=Tout-Tin.

Maximum Force (Max F) (BW %) is peak force in each foot subregion during loading.

Maximum Pressure (Max P) (kPa) is peak pressure in each foot subregion during loading.

Note that the variability of spatiotemporal, kinematic and plantar pressure parameters was also assessed.

3.2 Clinical assessment

American Orthopedic Foot and Ankle Score-hindfoot (AOFAS) is the most commonly used subjective outcome score in clinical practice and research. It is completed by the clinician, based on patient's response and physical examination [Kitaoka et al., 1994].

Foot and Ankle Ability Measure Score (FAAM) is a self-reported health related quality of life questionnaire for patients with foot and ankle pathologies. The score has ADL (activity of daily living) and sports sections [Martin and Irrgang, 2007, Borloz et al., 2011].

*EQ-5D*is developed by the EuroQol Research Foundation, it assesses quality of life based on 5 dimensions (Mobility, Self-Care, ADL, Pain and Anxiety) as well as visual analog score (VAS) for health status on the day of assessment [Hung et al., 2015]. All three questionnaires can be viewed in full in the Appendix II.

4 PhD thesis milestones

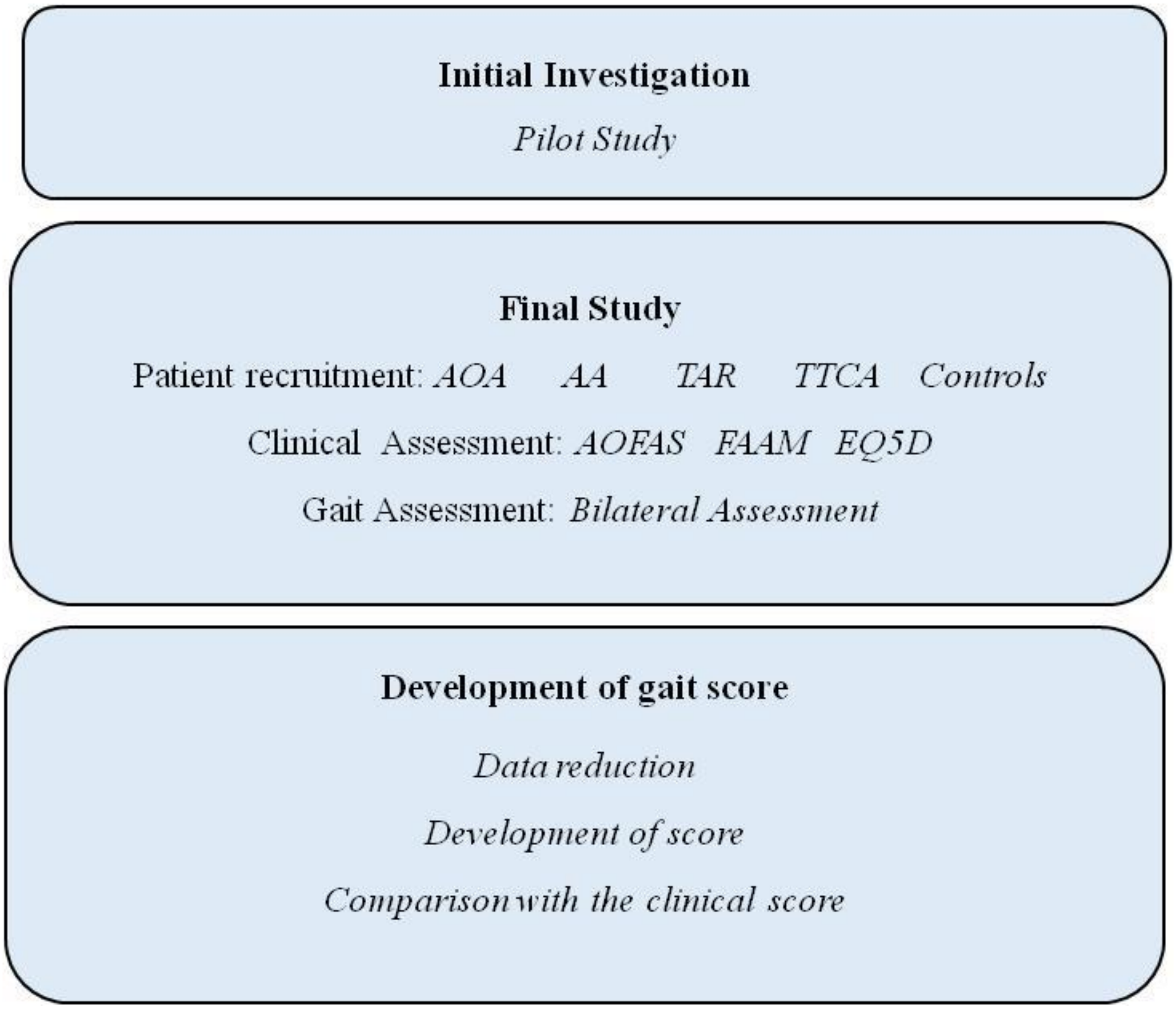

Figure 12: Milestones described in the following chapter.

4.1 Initial investigation

4.1.1 Introduction

To test the potential of gait parameter reduction in clinical practice, an initial study was performed in moderate to severe hallux valgus (HV) pathology. HV is a pathologic condition which includes a medial angulation of the first metatarsal together with a lateral angulation of the first toe and causes pain and difficulty in walking. Lapidus is a common surgical procedure to treat moderate to severe HV. The goal was to characterize gait in patients with HV and find clinically relevant parameters. Furthermore, the patients were followed 6 months postoperatively and assessed using the similar gait parameters to check if the reduced parameters add clinically relevant information. This particular condition was chosen for the initial investigation for the following reasons: 1) Moderate to severe HV is a frequently encountered pathology and is associated with a commonly performed surgery at our institution so that it offers a great potential patient availability; 2) This pathology is associated with sufficient pain to provoke a pathologic gait pattern; 3) Lapidus procedure allows returning to full weight bearing after 3 months facilitating, therefore, pre- and postoperative gait assessment within a relatively short period. The first hypothesis of the study was that it is possible to characterize gait in HV deformity with reduced set of parameters. Second hypothesis was that at early post op period of 6 months the reduced set of parameters will provide clinically useful information which is missed by the existing clinical assessments.

4.1.2 Method

Study included 26 feet with moderate to severe HV and 30 healthy feet from controls were assessed and compared. Further on, 10 randomly selected patients who underwent Lapidus correction were followed at 6 months postoperatively. Subjective assessment was performed using two foot and ankle specific questionnaires, FAAM and AOFAS-forefoot. Gait assessment encompassed the measurement of gait parameters including spatiotemporal (cadence, stance, inner stance events, double support, stride, speed, peak swing speed, toe off and heel strike pitch angles) kinematics (sagittal, coronal and transverse plane motion around first metatarsophalangeal joint (TO-FF intersegment) and total foot (FF-SH intersegment). Lastly plantar pressures parameters including total contact duration, maximum force and pressure in 10 foot regions as explained earlier. Assessment method was same as described earlier in the methodology.

For the first part of the study, comparison between controls and the pathologic group was performed using the Wilcoxon rank-sum test. Furthermore, the gait parameters, showing a significant difference with the controls, were then filtered via forward stepwise regression to obtain the most clinically relevant gait parameters for HV deformity which could help describe gait deviations in the pathology. The correlation between the filtered gait parameters and FAAM and AOFAS scores were also assessed using Spearman's correlation coefficient [Bluman, 1997].

For the second part of the study, preoperative versus postoperative comparison is performed using the Wilcoxon rank-sign test while comparison of the postoperative outcome with the controls were performed using the Wilcoxon rank-sum test. For all comparisons level of significance was set at $p<0.05$ [Bluman, 1997].

4.1.3 Results

Based on the statistical outcome, out of the studied gait parameters, 9 relevant gait parameters were found, including: cadence, speed, foot-flat phase, push-off phase, peak swing speed, toe-off pitch angle, first metatarsophalangeal joint (MTP1) motion TO-FF) around sagittal plane, total contact duration at hind foot and peak vertical force at the first toe. These parameters showed good correlation with the clinical scores (Figure 13), and were capable of clinically describing the pathology and postoperative prognosis. While post Lapidus, the gait parameters including the 9 clinically relevant parameters showed no improvement, in fact most of the 9 parameters showed deterioration at 6 months postoperatively representing existing altered gait post operatively. Detailed description of gait outcome for both HV and post Lapidus can be found in Appendix IV pages 118-131.

Clinical scores outcome both pre and postoperatively are given in Table 1. Significant improvement in radiographic outcome and AOFAS score was reported. While FAAM scores showed no difference in the functional outcome.

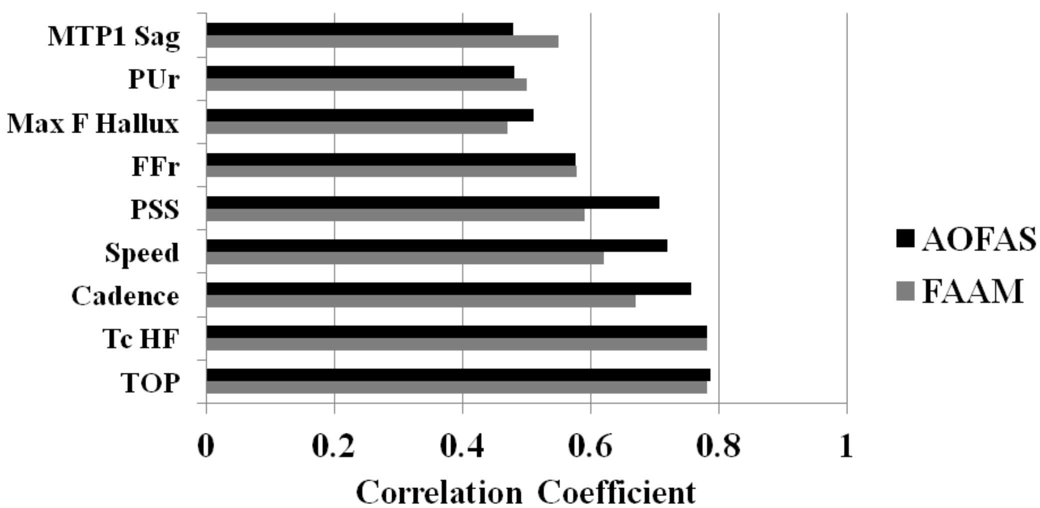

Figure 13: Correlation between gait parameters and clinical scores. All gait parameters showed significant correlation, >50%, with both foot and ankle clinical scores (p<0.05) [Chopra et al., 2015a]**.**

Table 1 : Clinical assessment preoperatively and 6 months postoperatively, mean (SD)

Clinical assessment	HV (Pre-operative)	Post Lapidus (Post-operative)
FAAM-ADL	73.46 (19)	74.46 (11.79)
AOFAS – total (100)	43 (8)	83 (14)*
AOFAS – pain	20 (0)	33 (5)*
AOFAS - function	25 (5)	37 (7)*
M1/M2 (º)	16 (2.1)	5.3 (2.7)*
HVA (º)	31 (5.6)	10.4(7.3)*
DMAA (º)	12 (4.0)	9.2 (4.3)

*represents ($p<0.05$), M1/M2: intermetatarsal angle, (HVA): hallux valgus angle, DMAA: distal metatarsal articular angle. AOFAS and Radiographic results reported significant improvement at 6 months postoperatively while FAAM score reported no improvement.[Chopra et al.]

4.1.4 Discussion

The study managed to successfully isolate the nine gait parameters most clinically relevant in characterizing gait variations in HV patients. These nine gait parameters also showed good correlation with the clinical scores which shows the clinical significance of these parameters in terms of functional outcome. It is also therefore assumed that these parameters alone can adequately describe abnormal gait mechanics in HV patients. For example, a gait with slow speed and low cadence is a sign of low activity level and can fairly describe the existence of apprehensive and or pain. Long foot-flat and short push-off duration, along with a slow peak-swing speed, describes altered toe propulsion during the terminal stance and early swing phase. Reduced toe-off pitch angle and MTP1 sagittal movement can describe the reduced mobility of the hallux and toes. The longer contact duration at the hind foot, explains the compensation due to the weak propulsion during weight transfer. Finally, weak vertical force at the first toe could help in understanding the partial loading of the hallux due to pain.

These nine gait parameters also showed no improvement in functional outcome of patients at 6 months post Lapidus when compared to the preoperative status. In contrast, the AOFAS forefoot score and radiographic results showed significant improvement at 6 months postoperatively. Hence, postoperatively, if rehabilitation is planned such that these 9 parameters could be brought back in-line with an accepted standard, this has the potential to provide good biomechanical prognosis.

4.1.5 Conclusion

The study concludes that;

1. Subjective assessment may over estimate functional outcome of the surgery.
2. Objective assessment adds information which has high potential clinical relevance in terms of improving rehabilitation.
3. The physical parameters give empirical evidence related to outcome of a surgery and therefore are a valuable component of the patient assessment.
4. Simplification of the gait assessment method using AGA method and reduction of number of assessed gait parameters to the most clinically relevant ones could promote gait assessment as part of clinical assessment.

5 Final study

5.1 Participant recruitment

The main study performed for the thesis purpose enrolled a total of 89 participants divided into three groups including: end-stage ankle osteoarthrosis (AOA) patients; patients who underwent three different types of surgery for end-stage ankle AOA surgeries; controls. The patients enrolled in the present work were protected under the ethics comity approval of the UNIL already obtained for the initial studies by Hossein Rouhani. All participants gave their informed consent. Details of participants' demographics are given in Table 2.

AOA group

Participants consisted of patients with isolated post-traumatic end-stage AOA stages 3 and 4 according to Kellgren and Lawrence, who were not affected by any other pathology of the spine and or lower extremities.

Surgical group

For AA and TAR subgroups, participants consisted of patients who have had isolated post-traumatic end-stage AOA, and undergone isolated AA or TAR, between 2003 and 2011. For TTCA, participants consisted of patients who have had combined OA of the ankle and subtalar joints or had failed TAR surgeries. All surgeries had been performed at the Orthopedic Department of the CHUV by a single surgeon, PD Dr. Xavier Crevoisier. Patients were excluded if they were affected by any other pathology of the spine and lower extremities.

Controls

The control population consisted of healthy volunteers who had no prior history of lower limb pathology, injury or surgery.

Table 2: Demographics of the study participants, mean (SD)

Demographics	AOA	AA	TAR	TTCA	Controls
No. of participants	15	15	20	15	24
Age (range)	65 (45-77)	64 (46-79)	63 (42-81)	64(56-81)	52(33-76)
Sex	5F/ 10M	9F/ 6 M	7F/ 13M	6F/ 9M	17F/ 7M
Weight	77.8 (12.5)	75.7 (15.7)	81.2 (14)	81.9 (15.3)	69.6 (15)
Height	166.7 (8.4)	164.9 (8.8)	170 (7.6)	171.9 (8.3)	170 (7.8)
BMI	27.9 (3.4)	27.5 (5.1)	28.5 (7.9)	27.7 (4.7)	24.1 (4.3)
Post-surgical follow up	-	4.7 (2.7)	2.7 (2)	2.5 (2)	-

5.2 Clinical assessment

The functional status of all study participants according to the three subjective questionnaires is given in Table 3. Note that notably low AOFAS score in AA and TTCA patients is due to the mobility subscale in the "Function" section of the score. Nonetheless a comparable functional status is reported in all three surgical groups, while a lower score is reported for AOA patients, as one would expect. These results also suggest that, the further gait comparison between groups would not have bias as the functional status of the surgical groups is similar.

Table 3: Clinical Assessment of the study participants, mean (range)

Clinical scores	AOA	AA	TAR	TTCA
AOFAS-total	48 (31-72)	66.8 (61-74) *	82 (63-100) *	61 (52-86) *
AOFAS-Pain	12 (0-20)	24.5 (20-30)*	30 (20-40) *	28 (20-40) *
AOFAS-Function	31 (17-42)	32.7 (30-36)	42 (27-50) *	26 (10-36)
FAAM-ADL	61 (32-90)	68.8 (37.5-97.5)	75 (45-97.5) *	72 (48-100)
EQ-5D	0.47 (-0.14-0.76)	0.60 (0.08-0.73) *	0.66 (0.16-1) *	0.57 (0.08-1) *

* represent significant difference from the AOA group.

5.3 Gait assessment

Gait assessment included two walking trials at a normal walking speed over a 50m long hospital corridor with each side being tested individually. The following sections details the main gait results for each group. More in-depth analysis can be found in [Chopra et al., 2014], [Chopra, 2015b], [Chopra, 2015a] (see Appendix IV, pages 132-167).

5.3.1 Spatiotemporal parameters

Speed

Previous studies, on health status of patients with chronic diseases [Studenski et al., 2011], have found walking speed to be a useful parameter in determining functional status of the patients. Furthermore, strong correlation has been observed between walking speed and patient mortality [Studenski et al., 2011]. A linear relation has also been reported between walking speed, stride length and cadence [Lelas et al., 2003, Kirtley et al., 1985]. Figure 14, shows the average walking speed, stride length and cadence of each study group. In comparison to the controls, case groups consistently reported a reduced walking speed with an inherent low stride length and reduced cadence. Among the three surgical groups, TAR patients reported the fastest walking speed, longest stride length and highest cadence.

Inner stance events

Percentage of inner stance events for all study groups are presented in Figure 15. A notable difference is seen in foot-flat and push-off durations in all three surgical groups on both operated (Op) and unoperated (Unop) sides, resulting in longer flatfoot and shortened push-off durations.

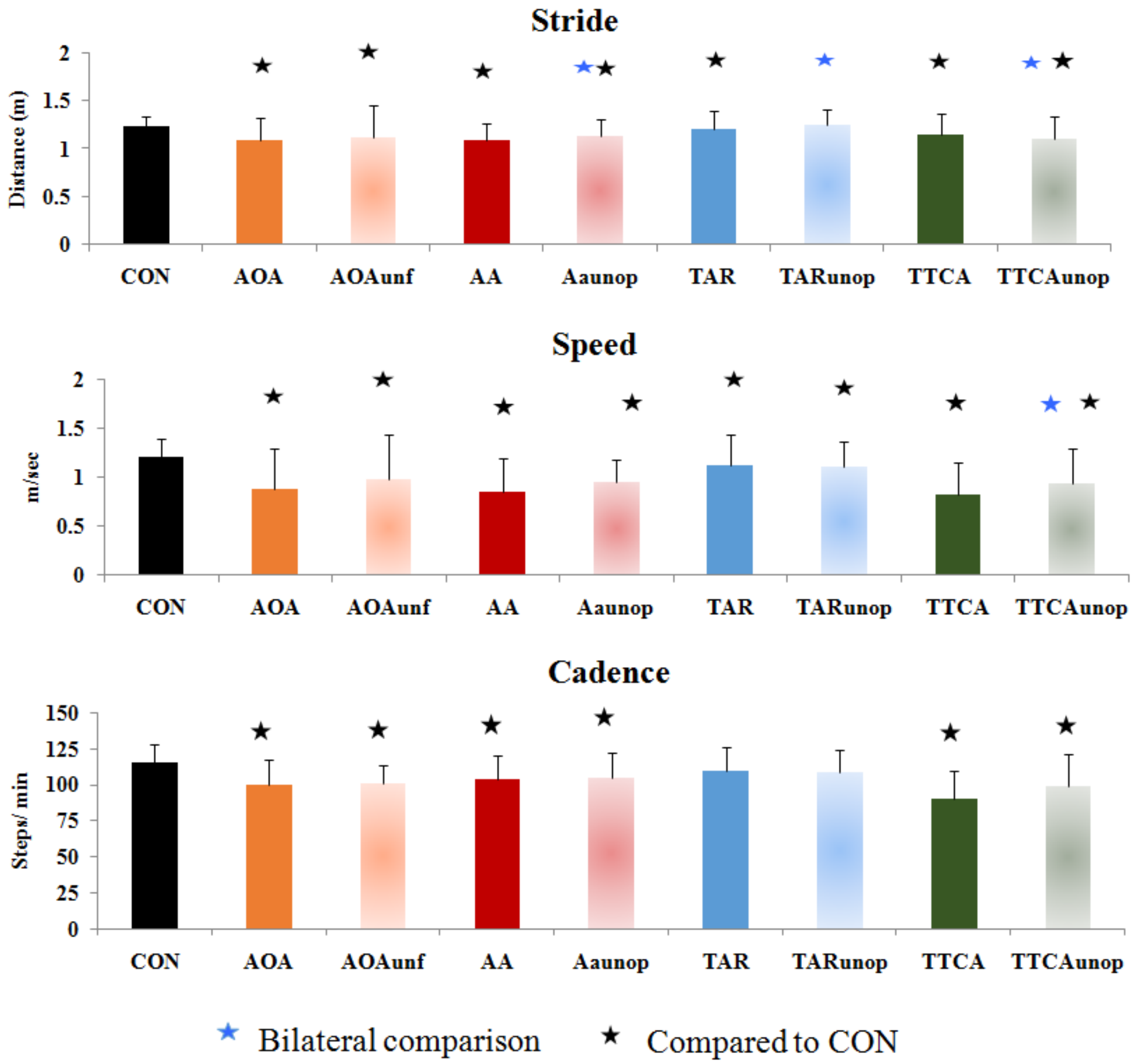

Figure 14: Average walking speed, stride length and cadence with SD of all study groups. The discussed linear relationship between speed, stride and cadence is also confirmed. Stars represent significant difference ($p<0.05$).

The initial and terminal contact during the stance phase is reported in terms of HSP (loading angle) and TOP (push-off angle), respectively (see Figure 10). Figure 16 shows the HSP and TOP angles for all study groups. The results show a reduced TOP in all case groups in comparison to both controls and their unaffected (Unaff)/ Unop sides. A reduced TOP is the consequence of the longer foot-flat duration which leads to a reduced loading of the hallux. In contrast to TOP, HSP showed mixed results between groups. It can be noted that fusion surgeries lead to different bilateral HSPs with a reduced angle on the Unop side, while TAR and AOA patients generally showed bilateral symmetry.

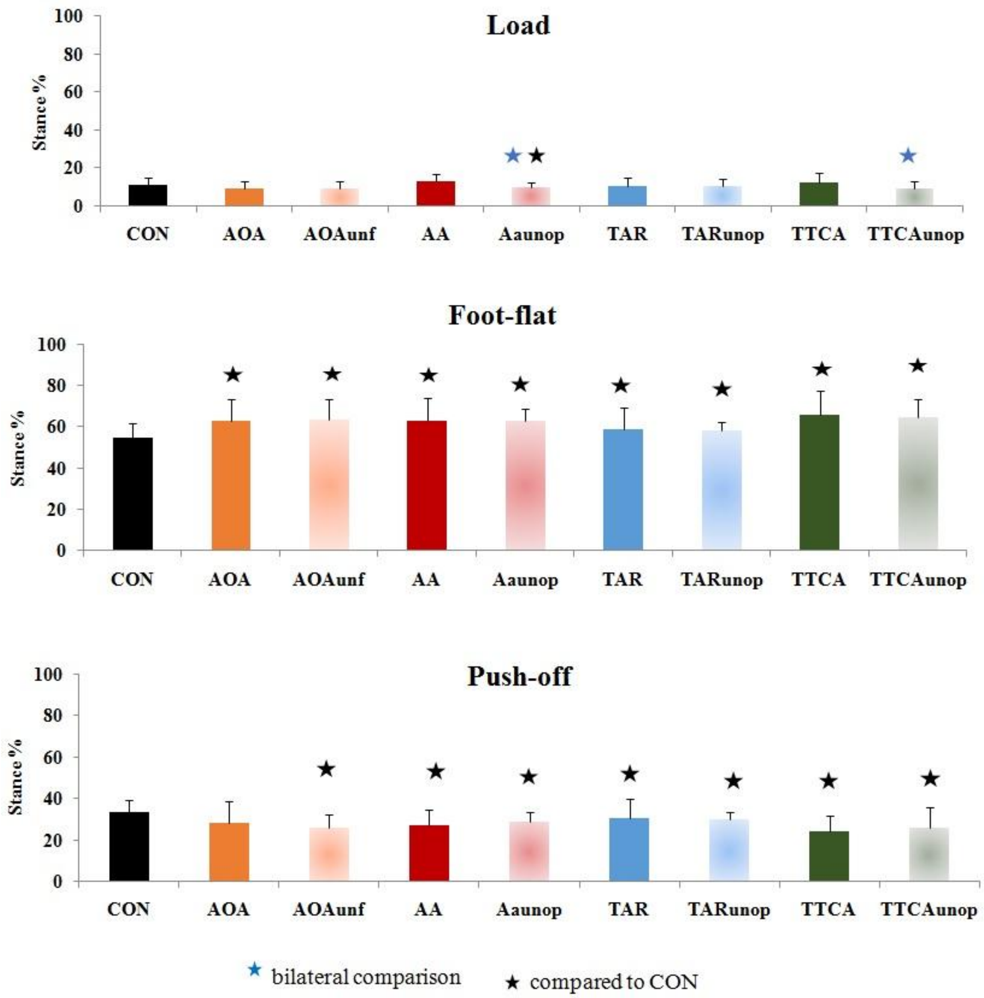

Figure 15: Inner stance events for controls and the two sides of each case group. Foot-flat and push-off duration in both sides of all case groups have shown visible difference with the controls. Stars represent significant difference ($p<0.05$).

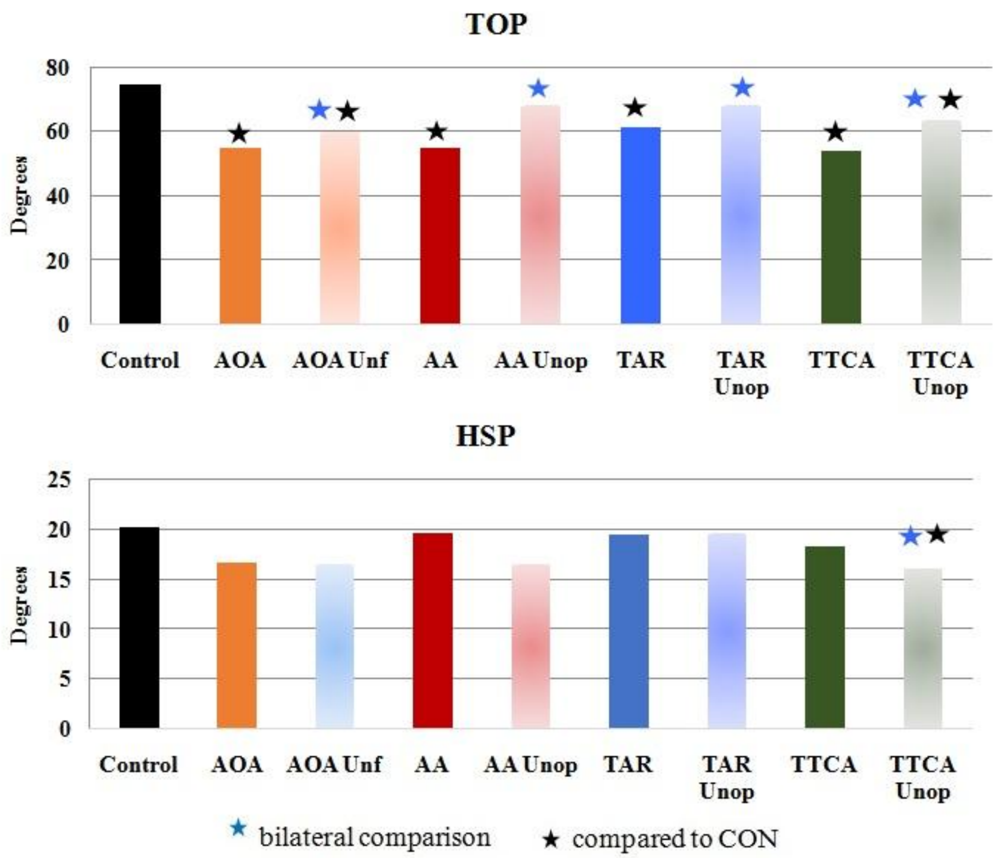

Figure 16: Toe-off pitch (TOP) and Heel-strike pitch (HSP) angles. Results show, better bilateral outcome in HSP in comparison to TOP. For easier readability results are displayed using two different scales. Stars represent significant difference (p<0.05). Note that TOP angle is 3-4 times larger than HSP as the former is followed by the swing phase.

5.3.2 Plantar pressure parameters

The assessment of joint loading during dynamic activity is a valuable tool for understanding weight bearing joints, as abnormal loading is related with the wear and tear of joints causing progressive degeneration. For the knee joint, several studies have attempted to reduce knee loading to prevent the progression of OA [Fregly, 2012, Kinney et al., 2013]. The foot plantar pressure assessment can detail loading anomalies, which could be studied by dividing the foot into different subregions. For example, in healthy adults, their loading pattern follows the following trend; hindfoot medial to midfoot lateral to forefoot central, and lastly to the hallux during push-off. The peak loading pattern in controls and the altered loading pattern in the fusion surgery groups can be seen in Figure 17. Results report an altered loading pattern and or magnitude at different foot subregions in the case groups. Below plantar pressure outcome for the four case groups are presented and compared with controls and their contralateral normal sides.

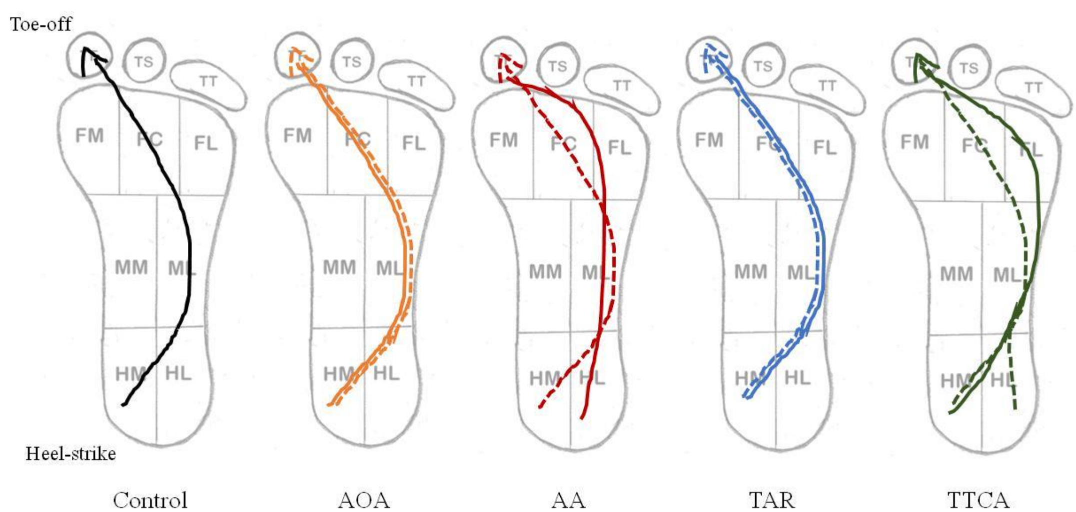

Figure 17: Peak pressure pattern of each group during stance phase. Solid line represents the Aff/ Op side and dotted line represents Unaff/ Unop side. AA and TTCA show a significantly altered peak pressure pattern for the Op side. The Unop side of TTCA showed equal peak pressure over whole of hindfoot.

Ankle osteoarthrosis

In comparison to the controls, AOA patients showed significant variations in 5 subregions for Tc, 4 subregions for Max F and 3 subregions for Max P on the affected (Aff) side and, on the Unaff side significant difference was reported in 6 subregions for Tc, 5 subregions for Max F and 2 subregions for Max P (Figure 18). All parameters show a reduced loading at the hallux. Comparing the Aff and Unaff side, difference was reported in all three parameters, Tc, Max F and

Max P, in the toe subregions. Above described results suggest the importance of assessment of complete foot for ankle pathology as, foot and ankle being a closed chain system, biomechanical alteration at one joint leads to adaptation in other surrounding joints. Further detail can be found in [Chopra, 2015a] (Appendix IV, pages 157-167).

Ankle arthrodesis

AA patients show a variation in Tc at 4 subregions as well as for Max F at 4 and Max P at 6 subregions of their Op side when compared to healthy controls (Figure 19). A lateral shift in loading pattern is also reported at the hindfoot on the Op side (Figure 17). The Unop side of AA patients showed differences in Tc at 9, Max F at 1 and Max P of 5 subregions. Such asymmetry is expected to have an undesirable effect on the contralateral foot in the long run. An Op to Unop side comparison also reported significant differences in Tc at 8 subregions as well as for Max F and Max P in 4 and 6 subregions, respectively. This clearly shows gait asymmetry, which is representative of a limping gait pattern. Further details can be found in [Chopra, 2015b] (see Appendix IV, pages 140-156).

Total ankle replacement

In TAR patients, when compared to the healthy controls, the Op side showed significant differences in Tc for 5 subregions, for Max F and Max P at 4 and 2 subregions, respectively, and the Unop side showed significant differences in Tc for 3 subregions as well as Max F and Max P at 2 subregions each (Figure 20). Furthermore, a reduced loading was reported at the midfoot lateral region on both sides. Op to Unop comparison shows relatively good symmetry with major differences for Tc at the TS, Max F and Max P at HL. The loading pattern of both sides is also seen to be similar to the controls. Further detail can be seen in [Chopra et al., 2014] (see Appendix IV, pages 132-139).

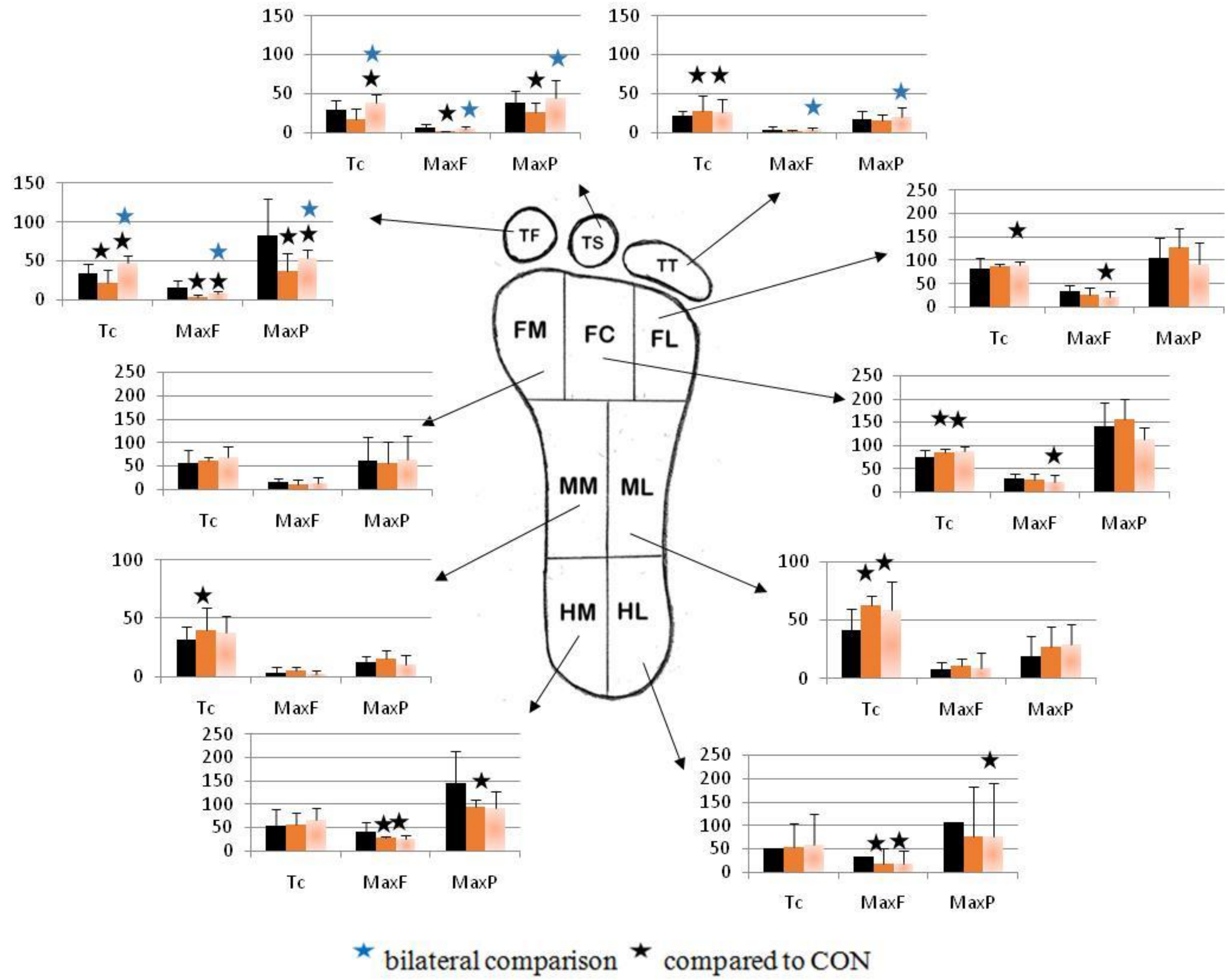

Figure 18: Bilateral total contact duration (Tc) (% St), Max Force (Max F) and Max Pressure (Max P) in 10 foot subregions for AOA patients. Black represents control, orange represent AOA Aff side and Orange light represent Unaff side AOA. Stars represent significant difference (p<0.05). Gait symmetry can be seen except for the toe subregions.

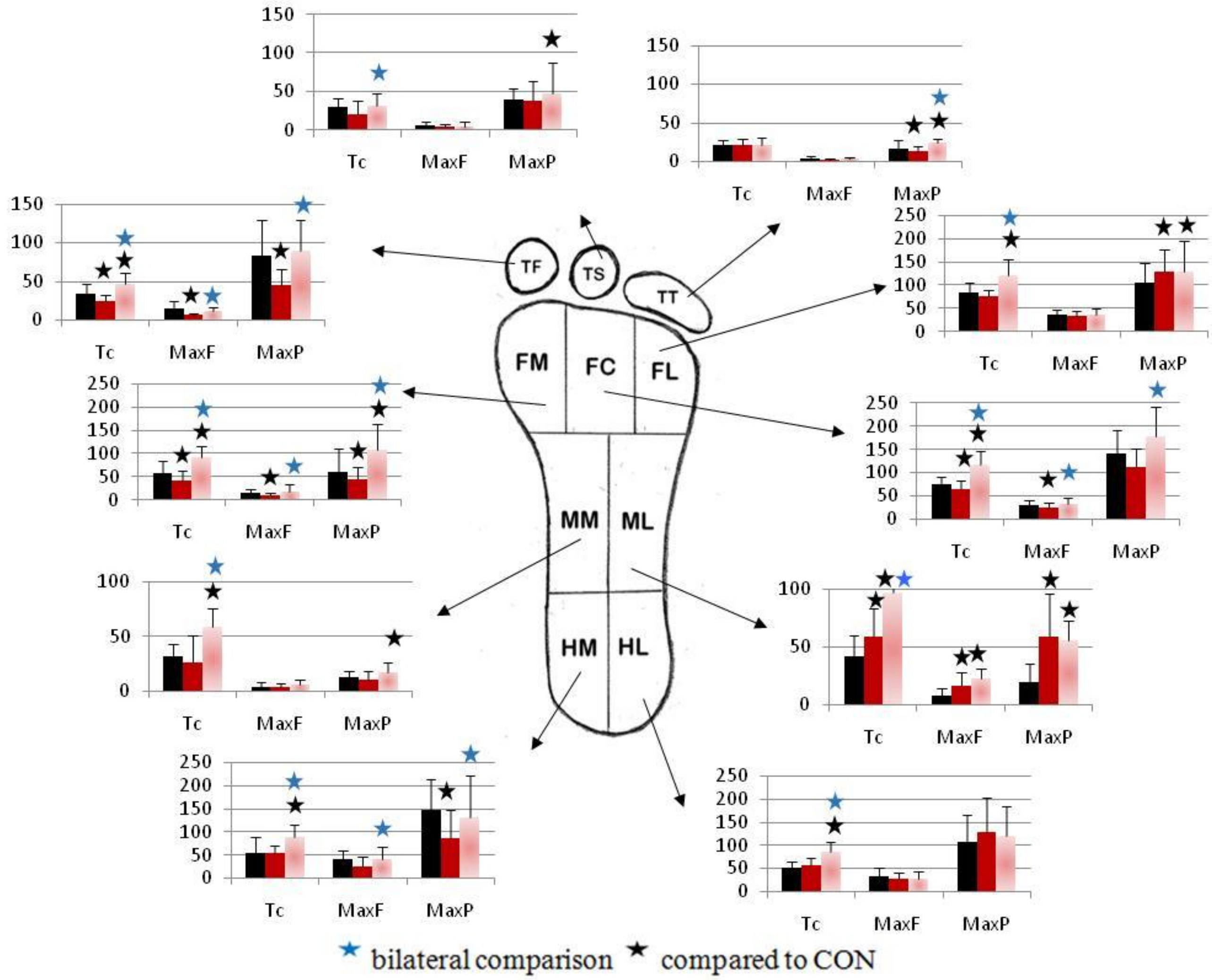

Figure 19: Bilateral total contact duration (Tc) (% St), Max Force (Max F) and Max Pressure (Max P) in 10 foot subregions for AA patients. Black represents control, red represent AA Op side and red light represent Unop side. Stars represent significant difference (p<0.05). Bilateral gait symmetry is seen to be altered significantly over all 10 subregions.

Tibiotalocalcaneal arthrodesis

Lastly, in TTCA patients when compared to controls Op side showed differences in Tc, Max F and Max P at 5,3 and 3 subregions, respectively, and Unop side showed difference in Tc for 5 subregions as well as for Max F and Max P at 1 subregion each (Figure 21). Furthermore, both sides showed differences in parameters in similar subregions when compared to the controls except Tc and Max P at toe regions. Op to Unop side comparison reported a difference only in Tc for second toe region, suggesting good gait symmetry. Note that, unlike AA the loading pattern at the hindfoot is seen to be preserved following TTCA. Further detail can be seen in [Chopra, 2015b] (see Appendix IV, pages 140-156).

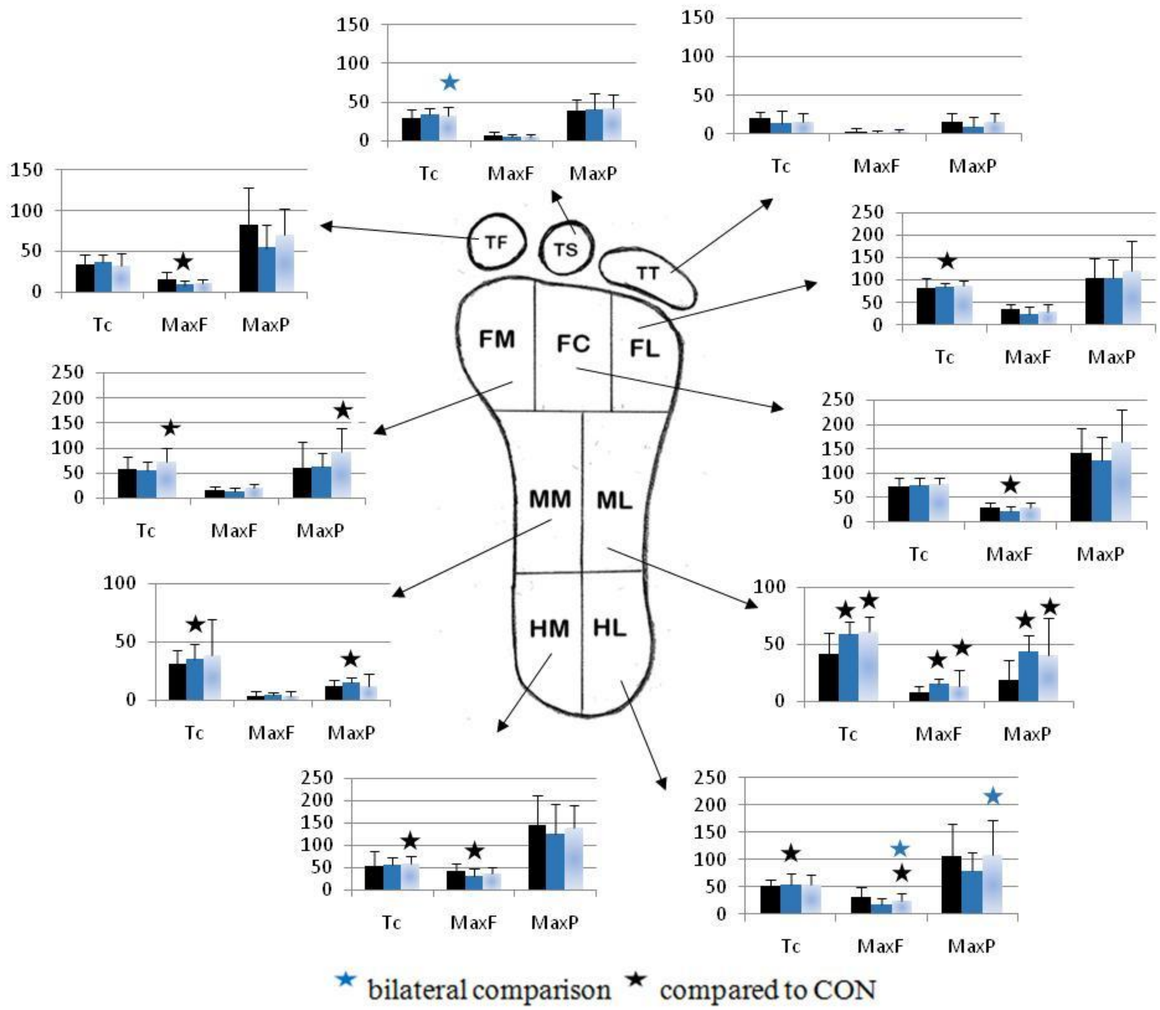

Figure 20: Bilateral total contact duration (Tc) (% St), Max Force (Max F) and Max Pressure (Max P) in 10 foot subregions for TAR patients. Black represents controls, blue represent TAR Op side and blue light represent Unop side. Stars represent significant difference (p<0.05). Bilateral gait symmetry is seen to be preserved in TAR patients and is comparable to the controls.

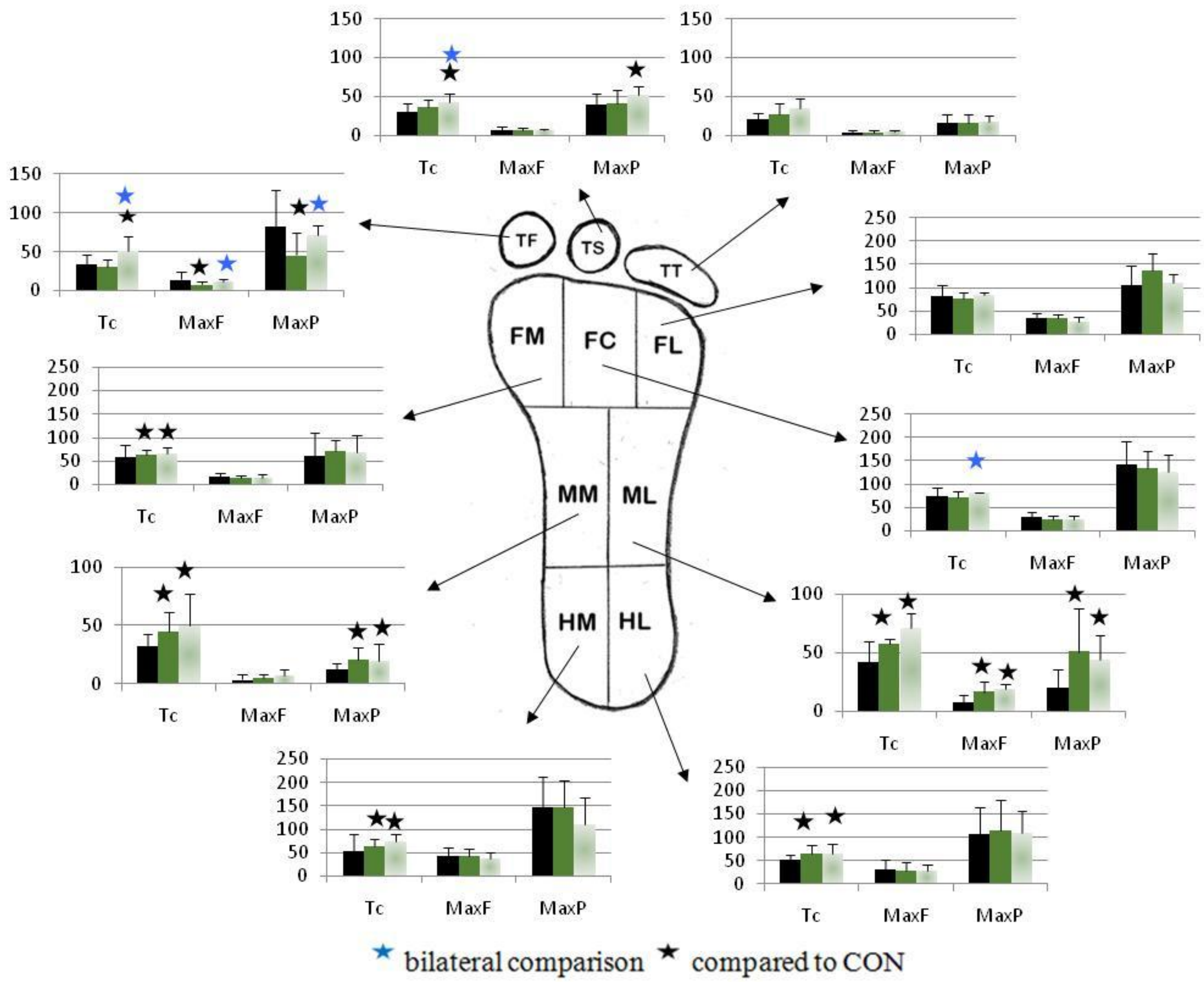

Figure 21: Bilateral total contact duration (Tc) (% St), Max Force (Max F) and Max Pressure (Max P) in 10 foot subregions for TTCA patients. Black represents control, green represent TTCA Op side and green light represent Unop side. Stars represent significant difference (p<0.05). Bilateral gait symmetry is seen to be preserved except for the hallux subregion.

5.3.3 Kinematics

Joint kinematic results provide information regarding the freedom of motion around a joint. End-stage AOA is known to cause joint stiffness making kinematic assessment an important tool to quantitatively assess joint restriction. However, walking function does not necessarily require a joint to move to its full range and any restriction detected by a passive range of motion test, if not severe, may not properly estimate functional restriction. Furthermore, during goniometric assessment of ROM each joint is assessed individually which gives little to no information regarding how different intersegments coordinate together. Nonetheless the measured mean intersegment range of motion in all three planes for the study groups is given in Table 4.

As seen, the majority of the motion occurs in the sagittal plane during forward propulsion of the body while walking. Notable differences were reported in the case groups compared to the controls. The Aff side of AOA patients showed reduced sagittal plane ROM in all four intersegments compared to controls. Among the surgical groups AA Op side notably showed reduced ROM in all intersegments in all planes, while their Unop side showed no significant difference at all. TAR Op side showed similar result as AOA patients reporting reduced ROM in all four intersegments in the sagittal plane, with the Unop side showed no difference. Lastly, TTCA Op side showed reduced motion in all intersegments in the sagittal plane, as well as for the HF-SH and FF-SH intersegments in the coronal and transverse planes. While, TTCA Unop side only showed a reduced ROM in the sagittal plane, at TO-FF and FF-SH intersegments. Note that body worn inertial sensors are, however, subject to drift error from accumulated signal noise while measuring sensors orientation angles [Takeda et al., 2014], particularly in the coronal and transverse planes [Rouhani et al., 2012].

Figure 22 shows the division of motion between dorsiflexion and plantarflexion during the stance phase of the gait cycle. A reduced plantar flexion can be seen at the end of the stance phase in most groups. Notably, the HF-SH intersegment of the Unop side of AA and TTCA groups showed no difference with the controls in terms of ROM, however, the movement pattern showed more similarity to the Op side than to the controls.

Table 4: Range of motion in three planes of each of the four intersegments, mean (SD).

Groups	Sagittal plane				Coronal plane				Transverse plane			
	TO-FF	FF-HF	HF-SH	FF-SH	TO-FF	FF-HF	HF-SH	FF-SH	TO-FF	FF-HF	HF-SH	FF-SH
Controls	39.4 (4.9)	27.1 (7.3)	14.3 (4)	30.2 (6.3)	12.3 (3.4)	11.5 (4.7)	13 (5)	17.1 (4.3)	7.1 (2)	7.3 (3)	9.1 (2.2)	14.5 (4.8)
AOA aff	27.6 (9.2)†*	17.8 (8)†	8.5 (3)†	16.8 (7)†*	10.1 (3.2)	9 (3.8)	7.8 (4.1)	12.9 (4.2)	9.1 (2.3)†	6.1 (2.3)	8.4 (2.5)	8.9 (3.1)†
AOA unaff	32.4 (7.8)†	22.8 (8.2)	11.4 (0.6)†	24.3 (5.8)†	11.5 (2.9)	6.1 (3.4)*	8.2 (2.9)	16.5 (4.5)*	9.5 (3.2)†	6.9 (1.3)	7.1 (2.7)	10.9 (2.5)
AA Op	22.9 (6.5)†*	10.4 (4)†*	9.6 (5.3)†*	17 (5.3)†*	8.2 (3.1)†*	5 (1.6)†	6.7 (2.4)†*	7.2 (1.3)†*	9.5 (2.6)†	3.8 (1.7)†	5.3 (2)†*	5.9 (2.3)†*
AA Unop	36.1 (6.4)	19.9 (5)	12.2 (5.6)	27.1 (4.1)	11.6 (3.4)	6.5 (2.7)	10.6 (2.8)	13.5 (2.8)	9.6 (2.9)†	6.5 (2.2)	9.3 (2.7)	10.1 (4.3)
TAR Op	33.2 (9.3)†*	16 (3.9)†	9.4 (3.8)†	19.1 (5.1)†	11.2 (3.8)	8.1 (4)	9.4 (3.7)*	11.1 (4.6)	9.6 (3)†	5.4 (2.5)	7.8 (1.6)	8.8 (3.1)
TAR Unop	38.1 (7.4)	24.9 (7.2)	14.6 (4.3)	28.6 (5.8)	12.1 (2.3)	10.8 (6.3)	13.7 (3.9)	16.6 (3.5)	8.4 (2.6)	5.1 (2.2)	9.9 (3.6)	9.5 (3.1)
TTCA Op	28.2 (2.4)†*	13.8 (2)†	5.8 (1.1)†*	15.8 (1.2)†*	9.5 (1.8)†	5.5 (1.4)	7.1 (2.1)†	7.9 (1.8)†*	7.1 (3)	7.1 (2.6)	4.4 (2)†*	5.4 (2)†
TTCA Unop	32 (6.8)†	22.6 (6.3)	14.9 (6.1)	28.5 (3.2)†	9.1 (2.8)†	9.2 (6)	10 (4.4)	17.7 (5.7)	6.5 (2.5)	8 (1.8)	8.3 (1.1)	7.7 (3.3)†

† comparison to controls ($p<0.05$), * Aff/Op vs Unaff/Unop ($p<0.05$). TO-toes, FF-forefoot, HF-hindfoot, SH-shank

Furthermore, the FF-SH intersegment of the Unop side of both AA and TTCA groups showed plantar flexed position during heel strike, unlike controls, while the Op side shows a neutral motion. For TO-FF intersegment all four groups reported reduced ROM and at the end of the stance reduced dorsiflexion was seen in AOA, AA and TTCA groups.

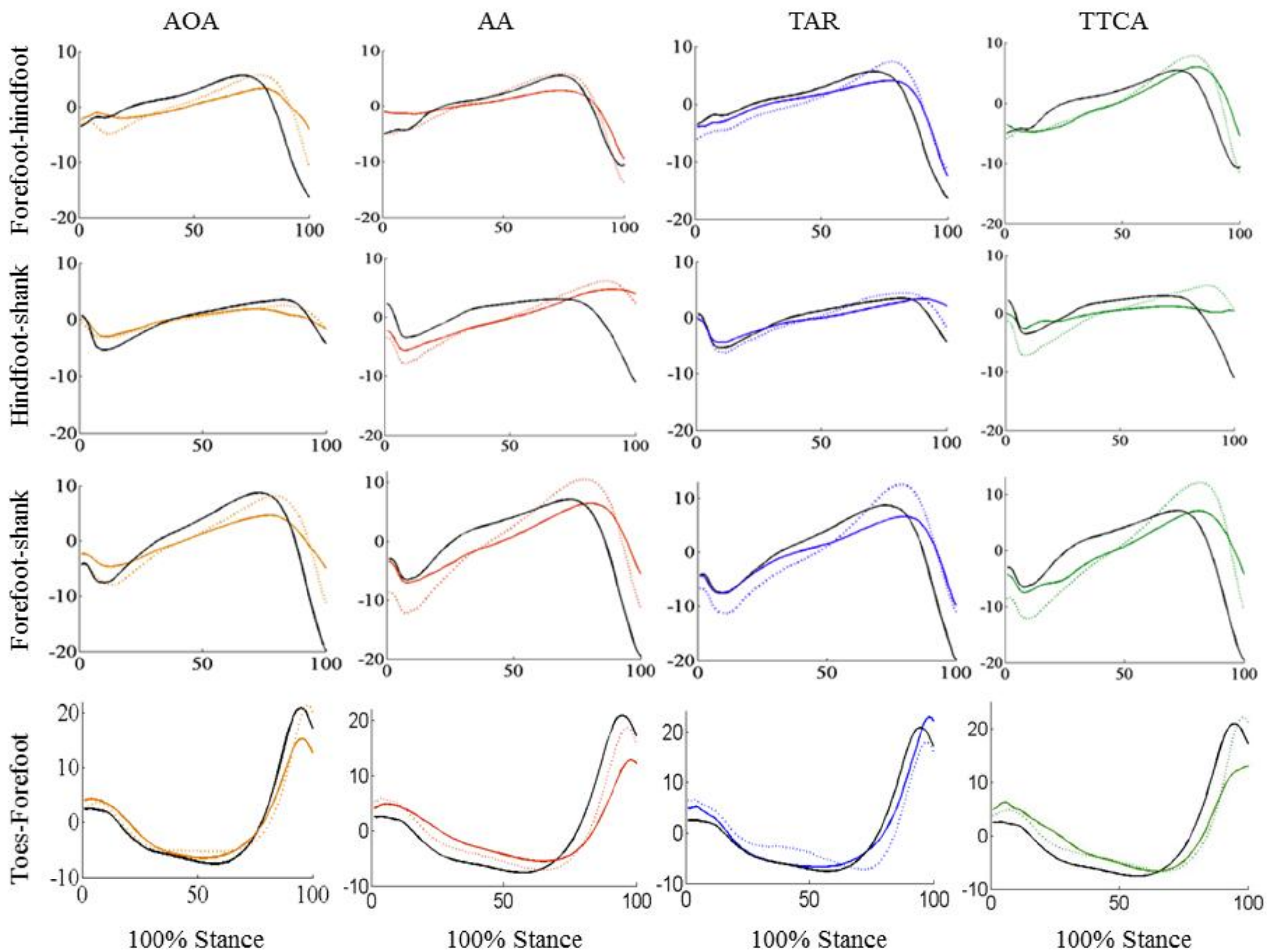

Figure 22: Range of motion in sagittal plane for three intersegments over 100% stance duration. Positive angle represents dorsiflexion and negative represents plantar flexion. Bold lines show controls and case groups accordingly, dotted line show the Unaff/ Unop side.

Continuous relative phase

CRP allows one to look at intersegment coordination throughout the gait cycle, providing an otherwise missed qualitative perspective of the ankle dynamics. CRP is calculated in accordance with the following equations,

$$\Phi = tan^{-1}\left(\frac{\omega}{\theta}\right), \tag{2.2}$$

where Φ is the phase angle, ω is the angular velocity and θ the static angle and the CRP is the difference in phase angle between segments,

$$CRP = \Phi_2 - \Phi_1. \tag{2.3}$$

An example following the derivation for the forefoot-hindfoot intersegment is shown in Figure 23. The final plot shows the CRP for the full duration of a gait cycle, with positive values representing distal rotation and negative values representing proximal rotation. CRP was calculated for the three main foot segments of both sides for all groups. Investigation was only in the sagittal plane, due the given importance by previous significance results. Results can be found in Figure 24.

Forefoot-hindfoot coordination

Most notably, TAR is the only surgical option with both sides showing initial contact results similar to the controls. AA patients only show comparable results in the Op side, with their Unop side initial distal rotation comparable to AOA patients. Furthermore, both sides of TTCA patients have a worse initial distal rotation than AOA patients. Looking at push-off peaks, both AA and TAR perform reasonably well in comparison to controls, however, TTCA patients show significant asymmetry albeit still an improvement on AOA patients which, in fact, show distal rotation for the Op side.

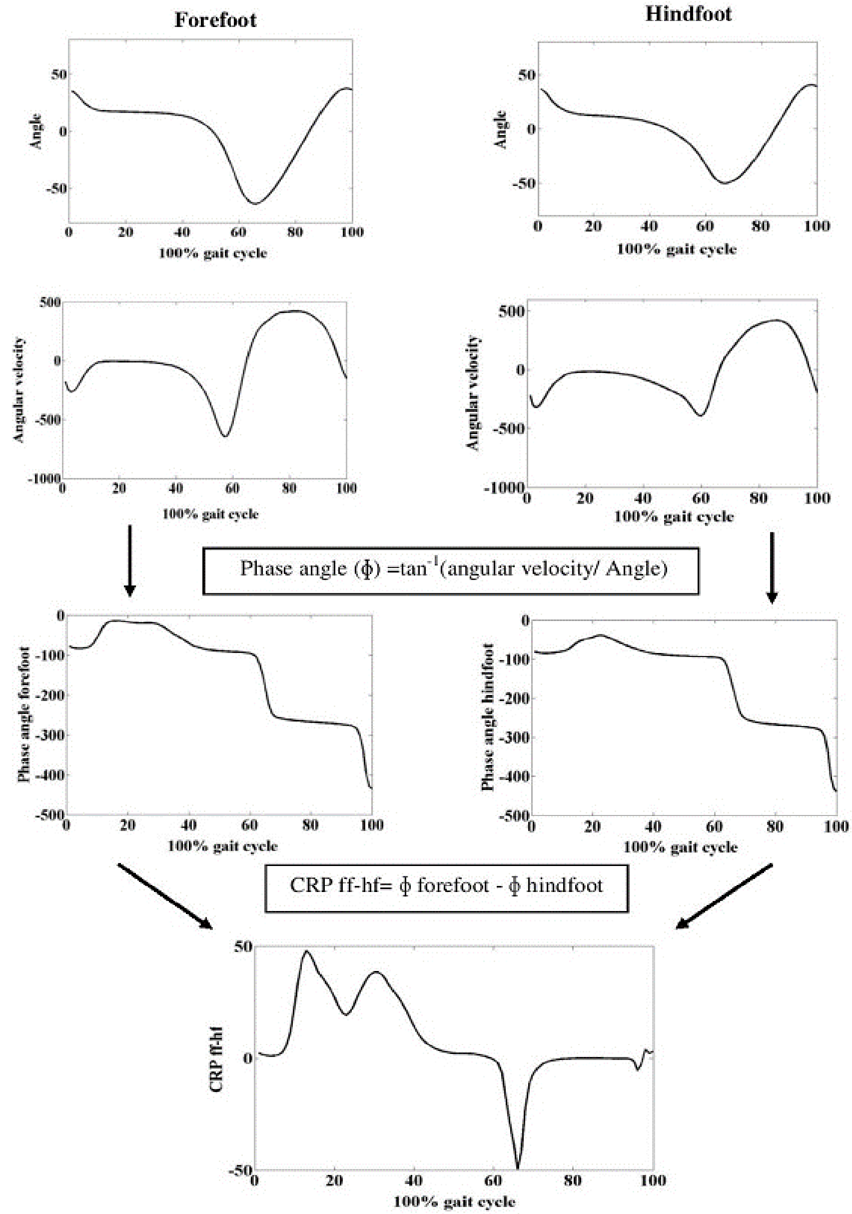

Figure 23: Example of CRP derivation for the forefoot-hindfoot intersegment. [Chopra 2015]

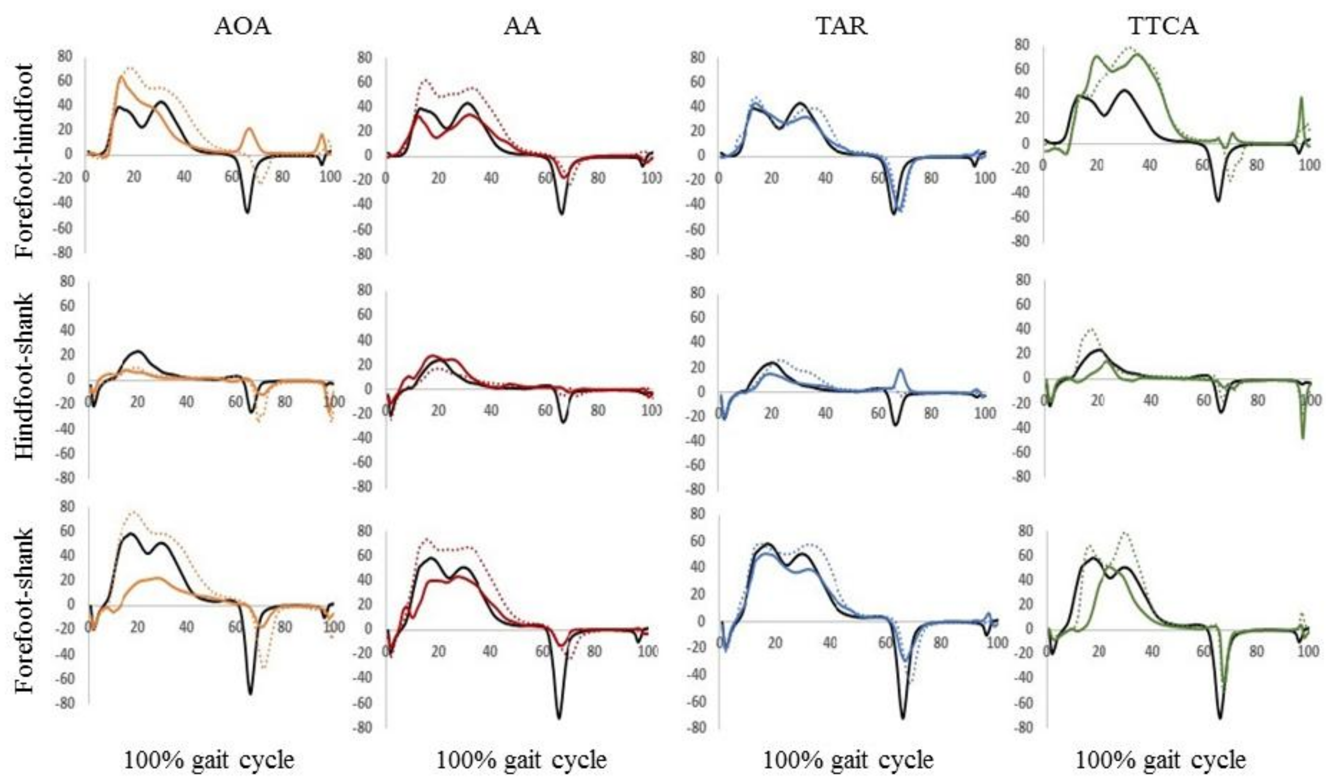

Figure 24: CRP curves for the three intersegments in sagittal plane. Bold lines show controls and case groups, accordingly and dotted lines show the Unaff/ Unop side

Hindfoot-shank coordination

In general, all surgical options appeared to have made significant improvements over AOA patients, bringing the ROM in the distal segment in-line with controls, with the exception of a notable asymmetry in TTCA patients. Looking at the push-off peaks, AA and TTCA both show a significant reduction in proximal rotation of their Op sides, likely due to joint fusion. However, TAR patients, in fact, showed significant asymmetry during push-off with a distal rotation observed at the Op side.

Forefoot-shank coordination

Again, all surgical options appeared to make significant improvements over AOA patients, with reduced asymmetry and a ROM of comparable magnitude to the controls in both initial contact and push-off. Of the three surgeries, TAR shows the best results with both Op and Unop sides being comparable to controls, see Appendix IV, pages 176-191.

5.3.4 Gait variability

Gait variability looks at the fluctuation in walking function [Hausdorff, 2005]. Notably, variability in spatiotemporal and kinematic parameters is found to be associated with an increased risk of fall in patients following hip and knee arthroplasty [Jorgensen and Kehlet, 2013, Kiss, 2010, Kiss, 2011]. The gait variability is calculated using the coefficient of variation, in accordance with

$$CV(\%) = \frac{stdev}{mean} * 100. \quad (2.4)$$

In the present study, [Chopra S., 2015] the effect of gait variability in AOA patients was investigated, before and after the surgical correction. In contrast to gait parameters, results showed little to no correlation between the clinical scores (Figure 25). In fact, FAAM score showed < 20% correlation with most gait variability parameters with exception of foot-flat variability. The study concluded that, unlike hip and knee OA, in AOA gait variability is not found to be an important parameter when determining the outcome of the ankle surgeries, see Appendix IV, pages 168-175.

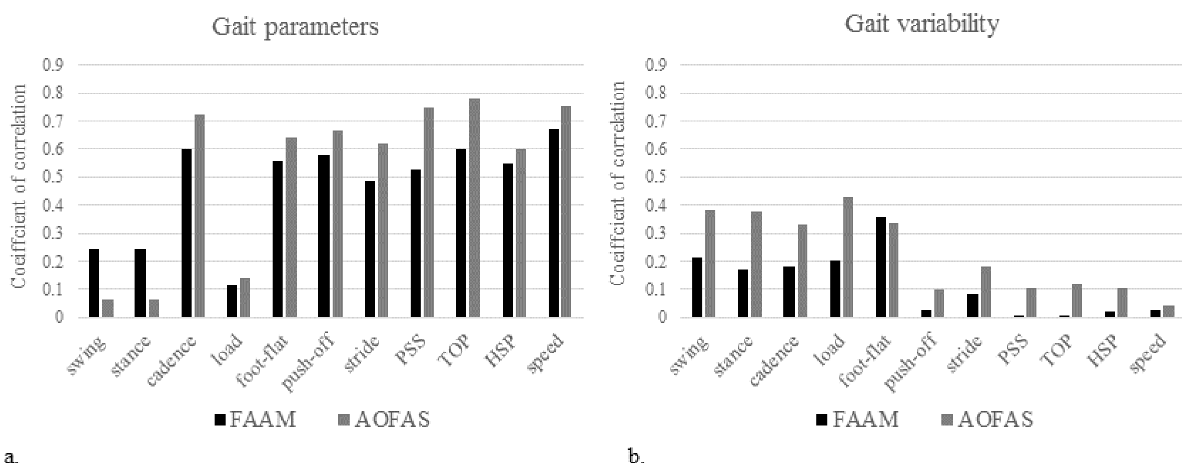

Figure 25: Correlation between AOFAS and FAAM with a. gait parameters, b. variability in gait parameters. Good correlation (> 40%) is reported between the clinical scores and gait parameters while weak correlation (< 40%) is reported for gait variability.[Chopra S., 2015]

6 Development of the gait score

6.1 Introduction

The final goal of the thesis was to develop a simple, yet robust objective assessment score which is both easy to use and can provide an accurate clinical representation of the patient's functional status in comparison to the existing subjective assessment methods. As previously discussed, the pilot study reported drawbacks in the use of clinical subjective scores which, though capture variation in functional status in patients with deformity, are not reliable enough to assess postoperative functional status. This is mostly due to the outcome of subjective questionnaires being highly weighted towards pain threshold and once the pain is reduced, the overall average outcome of the score tends to increase irrespective of the real functional ability of the patient. The pilot study also suggested that for clinical usability and simplicity it is important to reduce the number of parameters used for assessment to a more manageable amount, whilst retaining the majority of information. This section details the development of an objective gait score utilizing most clinically relevant gait parameters as well as showcasing its reliability and capability relative to subjective methods both in AOA and following its surgical corrections.

6.2 Method

Data from 80 participants including 15 AOA, 50 post-operative patients including; 15 AA, 20 total ankle replacement TAR, and 15 TTCA patients, and 15 controls were included. Detailed description of the study group is given in section 5.1. However, from the total 25 controls examined in this thesis, only 15 age matched controls were included in this part of the study in order to remove age related discrepancy in the development of the final gait score. Gait assessment was performed using the described ambulatory gait assessment system (detailed in section 3.1) clinical assessment was made using the two clinical foot and ankle specific (AOFAS, FAAM) and one global health status score (EQ5D) (detailed in section 3.2).

6.2.1 Data reduction

Primarily data reduction was carried out focusing on the AOA group and all the 48 gait parameters (detailed in section 3.1.1) were utilized. Firstly, gait parameters in AOA patients showing significant difference with age matched controls were identified using the t test (at $p<0.05$, 25 out of 48 parameters). The goal was then to further reduce this parameter set to find least number of parameters whilst maintaining a sufficiently strong correlation (> 0.7) to the complete parameter set. Note that, unlike the pilot study which used stepwise regression, this process was carried out using the principal component analysis (PCA), as PCA has been found to be a more robust method of multivariate data reduction, particularly for parameter sets with such widespread variances [Daffertshofer et al., 2004, Meyer et al., 2015].

Principal component analysis

PCA is the deliberate reduction in dimensionality of a data set, which consists of a large number of correlated variables, whilst retaining as much information as possible. This is achieved by transforming the data to a new set of variables, which are then ordered so that the first few retain the majority of initial information [Jollieff, 2012].

PCA starts with a mathematical transformation which results in a number of "components" equal to the number of original variables. Each component is an eigenvector, i.e. main axis, of the transformed parameter "subspace", with each component representing a specific percentage of data variance. Components are then ordered by percentage of variance and the number of *principal components* (PCs) is decided by a threshold of accumulated variance (topic specific). The remaining components are referred to as *residuals and* represent the square prediction error (Figure 26).Subsequent analysis of both PCs and residuals can be used to improve model accuracy by investigating the "lack-of-fit" (Q-statistic) as well as the "goodness-of-fit" (Hotelling T^2-statistic). In this study, we set >90 % of variance as the inclusion criteria for PCs in accordance with [Deluzio and Astephen, 2007, Jackson, 1991]. Note that, with such a high threshold, residuals are almost redundant and as such only the T^2-statistic analysis was used in data reduction.

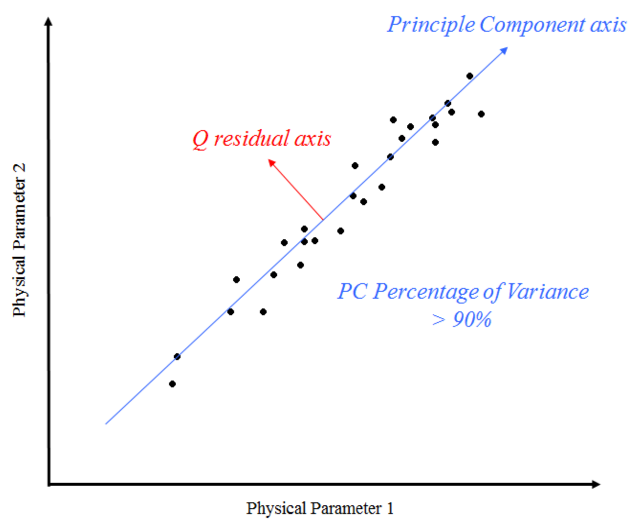

Figure 26: 2-D PCA visualization plot defining the principal component and residual, Q. Hotelling T^2-statistic

The Hotelling T^2-statistic calculates the distance between the theoretical central point of a base distribution and any another "subject" point within the parameter space. This allows one to express patient variation across all principle components in a single value. The Hotelling T^2-statistic is calculated following [Deluzio and Astephen, 2007, Deluzio et al., 1997],

$$T^2 = x^T(\boldsymbol{\Sigma}_n)^{-2}P^T x, \tag{2.5}$$

where x is the new observation, P is the space transform vector, n is the number of principle components and $\boldsymbol{\Sigma}_n$ contains the magnitude of all principle components. Figure 27 shows a simplified data elimination process using the T^2-statistics as it would be in 2-D, i.e. only two principle parameters (PP). It shows that if the T^2-statistic of both PP1&2 is equal to only PP1, then the influence of PP2 is almost zero suggesting that PP2 is not necessary in providing good correlation with the full data set. In such a situation, PP2 is removed.

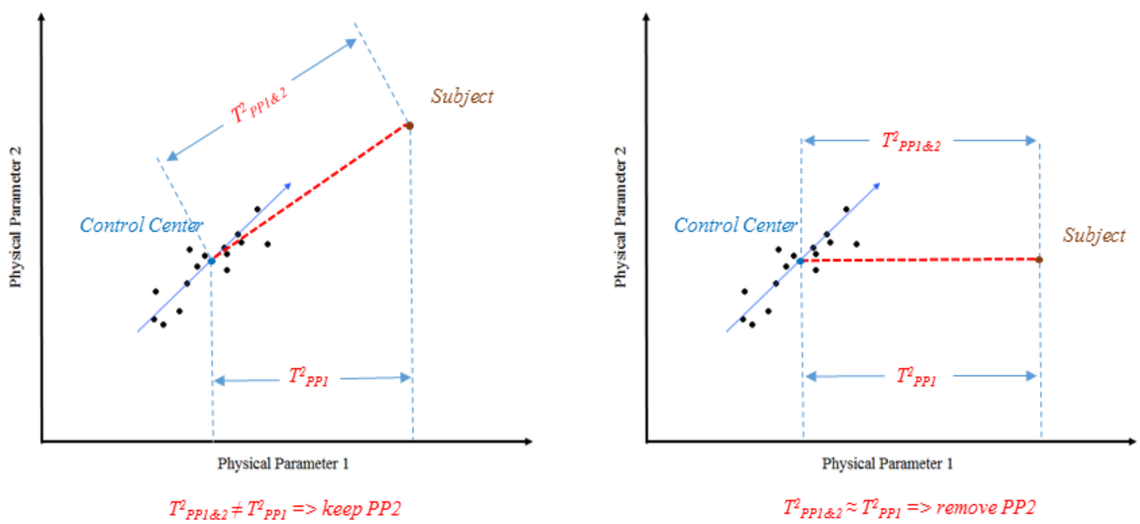

Figure 27: Parameter Reduction 2-D Visualization.

Data reduction steps

The complete process of data reduction is outlined in Figure 28. Note that this method is not solely applicable to this use, but could be used in any similar process of data reduction for various other pathologies and or different aspects of gait. Following the identification of 25 significant parameters, PCA was performed on both the full (48n parameters) and reduced (25 parameters) data sets. Pending acceptable correlation with the subject groups (> 0.9), i.e. AOA Aff, this process is repeated each time with removing the least significant parameter from the reduced data set until the correlation is below the defined threshold. Following this, PCA was carried out with the remaining reduced parameter set on *all* subject groups. If the correlation exceeds a more lenient threshold (>0.7) for all groups, the reduced parameter set is selected. However, if any do not exceed this level of correlation, the most significant missing parameters from these specific groups were identified and the whole reduction process is repeated accordingly until each side of all groups exceed the lenient correlation threshold.

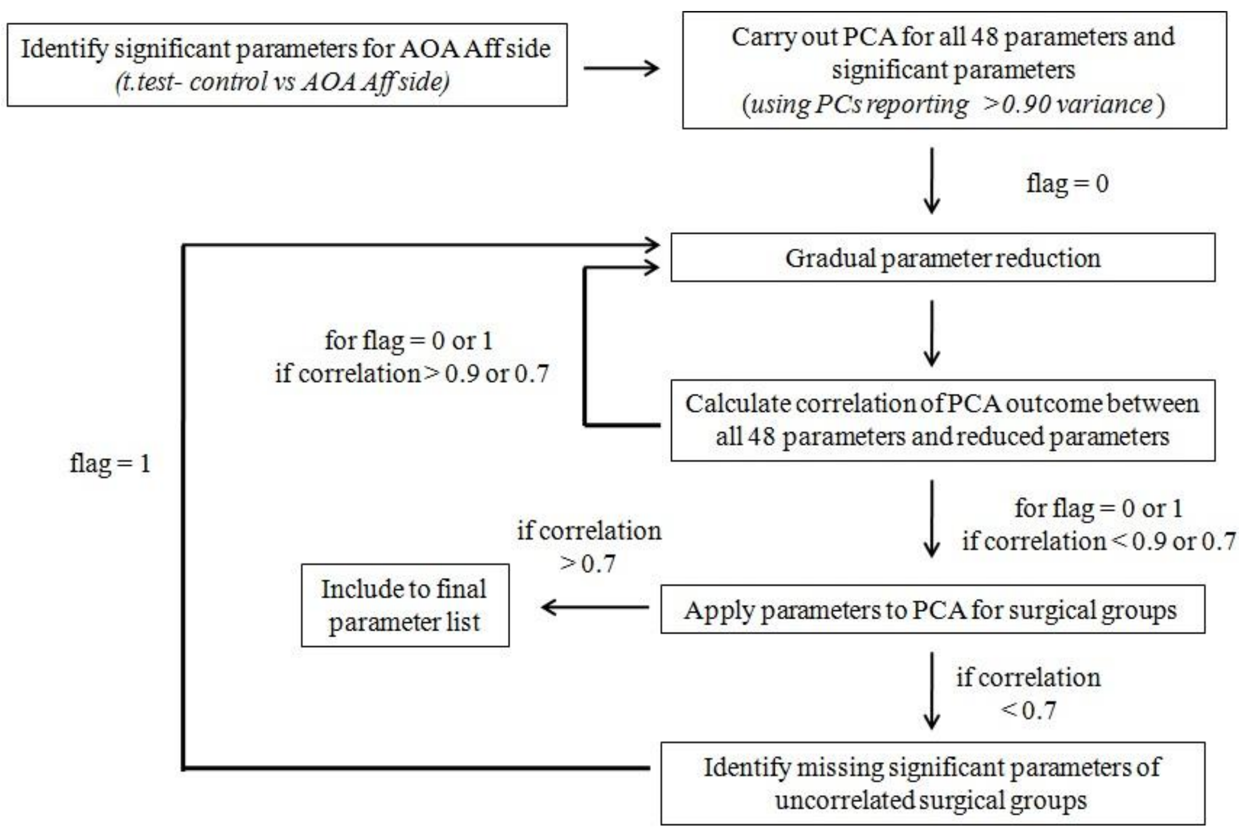

Figure 28: Flow chart of data reduction method.

6.2.2 Scoring system

The scoring system is based on each of the remaining parameters following data reduction. Score was provided to individual parameters and along with that final score was provided based on the individual scores. All the included parameters were weighted equally for the ease of interpretation of the individual scores. To define the range for the individual parameter scores Tukey's outlier detection method was used [Seo, 2002]. Tukey's method finds outliers by defining the range as follows – Q3+(1.5*IQR) and "Q1-(1.5*IQR) as *upper* and *lower inner fences* and Q1-(3*IQR) and Q3+(3*IQR) as *upper* and *lower outer fences*, with anything beyond the outer fences as *extreme outlier*"[Tukey, 1977], where Q1 and Q3 are the first and third quartiles of an age matched control group and IQR is the interquartile range. Based on the method, multiples of 1.5*control (IQR) are given a score between 0 and 3, with 0 representing optimal performance (very good), score of 1 representing good, 2 representing average and score of 3 reporting severe gait abnormality (Figure 29).

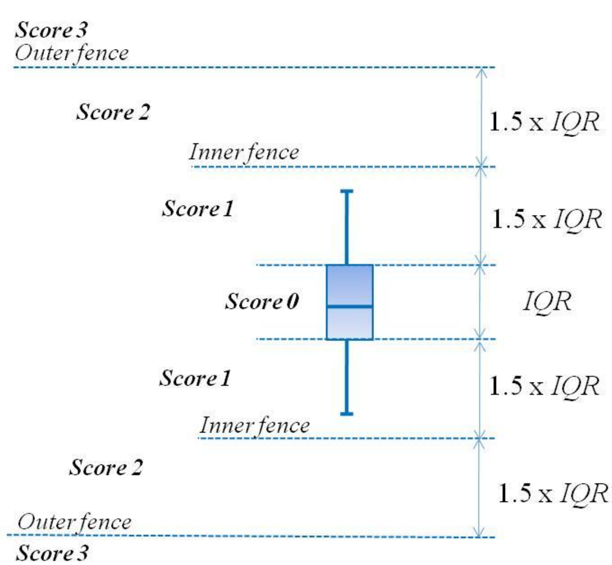

Figure 29: Scoring system utilizing the Tukey's outlier detection method. IQR: interquartile range, Q1: 1st quartile and Q3: 3rd quartile

6.3 Results

6.3.1 Data reduction

In this study, 15 parameters were originally identified with very high correlation to the AOA Aff group. This reduced set was then also found to show high correlation in all three groups including AOA, AA, and TAR. However, the TTCA Op group correlation was only moderate to low (0.45), which may be due to TTCA not solely being an isolated surgery for AOA, but patients may have also had subtalar pathologies. As a result the 5 most significant parameters of TTCA patients which were not already included were added and the reduction process was repeated until all four groups reported strong correlation (>0.7) (Table 5).The resultant final 17 parameters include; cadence, speed, peak swing speed, toe-off pitch angle, sagittal plane motion at toe-forefoot, forefoot-hindfoot and forefoot-shank intersegments, coronal plane motion at forefoot-shank intersegment, total contact at hindfoot lateral, midfoot lateral, forefoot central and first toe, maximum force at hindfoot medial, second and forst toe and lastly, maximum pressure at hindfoot medial and forst toe, with total contact at hindfoot lateral and forefoot central being included to sufficiently represent TTCA.

Table 5: Correlation coefficient (r) of reduced parameter sets with results using all 48 parameters.

No. of parameters	AOA	AA	TAR	TTCA
15	0.968 **	0.918**	0.81**	0.45
17	0.914**	0.80**	0.85**	0.76*

** represents p<0.001 and * p<0.01

6.3.2 Scoring system

Gait score results coincides with previous comparative studies of this thesis, with, on average, TAR performing significantly better than AOA, TTCA showing moderate improvement and AA showing little to no improvement. Detailed gait score for all the four case groups including AOA, AA, TAR and TTCA are given in Appendix III. Comparison between the outcome of the gait score and the clinical scores can be seen in Figure 30. The median gait score reported for AOA, AA, TAR and TTCA were 64 (17), 67 (10), 74 (4.5) and 71 (12), respectively, with significant improvement reported only in TAR group. On the other hand, AOFAS is shown to be giving an exaggerated outcome with significant improvement in functional status following all surgical corrections. FAAM on the other hand, reported outcome similar to the gait score when compared with the AOA group. However, for comparison between surgeries, FAAM reported similar outcome following TAR and AA in contrast to the gait score which reported significantly reduced gait score in AA compared to the TAR group. Difference between the outcome of F&A specific clinical scores were found to be similar as was reported in the pilot study.

Table 6 and Figure 31 show the correlation between the gait score and subjective scores. In general, little to no correlation is found (<0.4) which, following established issues with subjective scoring, is expected. Note that the subjective scores themselves even show little to no correlation with each other.

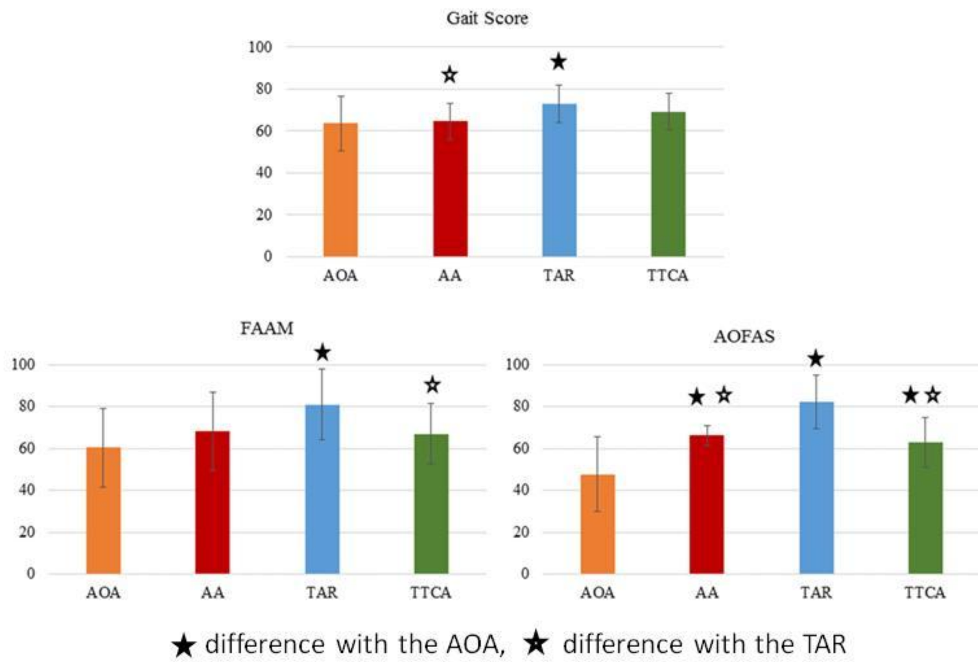

Figure 30: **Median and IQR of outcome of the proposed gait score and two clinical scores. represents significant difference with the AOA, represents significant difference with the TAR. It can be noted that outcome of both the F&A specific clinical scores differ. None of the two clinical scores coincide with the gait scores.**

Table 6: Correlation (r) between the scores for each of the four case groups is given with the level of significance (p)

Groups	Gait score vs FAAM	Gait score Vs AOFAS	FAAM vs AOFAS
AOA	0.07 (p=0.8)	0.28 (p=0.46)	0.40 (p=0.28)
AA	0.46 (p=0.15)	0.05 (p=0.88)	0.14 (p=0.67)
TAR	0.08 (p=0.76)	0.36 (p=0.17)	0.79 (p=0.0002)
TTCA	0.16 (p=0.64)	0.61 (p=0.046)	0.43 (p=0.18)
Combined	0.27 (p=0.07)	0.42 (p=0.003)	0.59 (p=0.35)

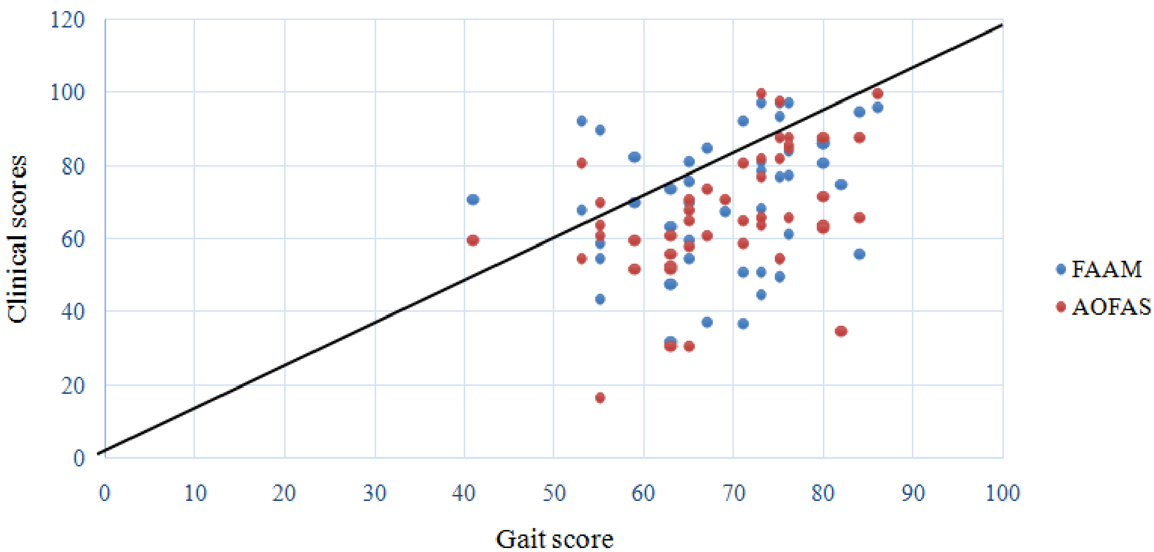

Figure 31: Correlation between gait score and the clinical subjective scores. All four group combined.

6.4 Discussion

The aim of this thesis was to develop a gait score for AOA and its surgical treatments. Improving upon the pilot study, a robust data reduction method using PCA was used to optimize the number of parameters, whilst retaining a high correlation of the selected parameters not just with the full data set of AOA but with all three surgical groups (AA, TAR and TTCA). It is of note that, in accordance with results presented earlier in this thesis, the importance of these 17 parameters in terms of gait alteration can be confirmed. In addition 7 of 9 parameters which were found to characterize HV is also found in the AOA gait score, suggesting the score has the potential to be used for other F&A pathologies.

Reduced parameter set rationale

Spatiotemporal parameters included were: cadence, speed, PSS and TOP. Speed and cadence, both highly correlated, have been shown to be parameters which can assist in health status diagnosis. Furthermore, both PSS and TOP have been shown to play important roles in maintaining both the walking speed and swing angular momentum which are essential in characterizing gait.

For kinematics, the gait score included: sagittal plane motion at TO-FF (hallux), FF-HF (midfoot) and SH-FF (ankle). This is because compare to the three planes, sagittal plane performs the majority of motion for propelling the body forward with each section of the foot being equally represented within this plane.

Plantar pressure parameters included: Max F and Max P at hindfoot medial, Tc, Max F and Max P at the first toe and Max F ofthe second toe as well asTc of the hindfoot lateral, midfoot lateral and forefoot central regions. All parameters together shows both impact force in the most important regions for pathological patients, hindfoot and toes, as well as gives general information about the contact duration of each major foot region.

All in all, each of the remaining parameters show essential information regarding pathological gait characteristics with no left out parameters giving information which is not already represented and or deemed important.

Scoring System

The decision to include individual parameter scoring along with the overall final score was to allow for an independent cross-reference to overall performance which could assist clinicians in quickly assessing particular issues for given individuals. Furthermore, the scoring system gave equal weightage to all the parameters in the gait score this might not be the best method in terms of statistics, however, from clinical perspective gait parameters are seen to be related to each other and alteration in one parameter has shown effect on other. In such scenario, giving more weightage to certain parameters over other would not seem beneficial. In fact this could make the interpretation of the score more complex.

In conclusion, the developed gait score is thought to be a robust, practical (quick and easy to use/assess/show progress), and reliable assessment method. Nonetheless, the responsiveness, reliability and repeatability of the score require further study. In particular, the score needs to be rigorously tested in greater study population and also for different foot and ankle pathologies.

7 Conclusion and perspectives

In recent years, research into orthopedic surgery has shown that objective assessment can be used to improve understanding of the biomechanical and functional status of a patient, both pre- and postoperatively. This, in conjunction with the recent development of a cost effective and portable ambulatory gait assessment (AGA) system, has brought forward the question of the potential for objective gait assessment for foot and ankle (F&A) surgeries in clinical practice, a field currently dominated by potentially error-ridden subjective questionnaires. As a result, this study was carried out to test the validity of such a system for use in clinical practice, including the development of an objective outcome score to complement and or rival such questionnaires.

7.1 Answering thesis questions

7.1.1 Identification of clinically relevant gait parameters

A pilot study, using the AGA system on patients with hallux valgus, showed that it is possible to quantitatively characterize a patient's gait with a reduced parameter set, 9 of the 47 parameters. Another investigation also found that for a qualitative interpretation of overall functionality, foot intersegment coordination can be very useful. Finally, in developing a gait score, progressing on used methods of identifying parameter significance, it was shown that it was possible to characterize AOA and surgical patients with only 17 of the 48 parameters. Overall, a clear and robust method of identifying clinically relevant gait parameters was established.

7.1.2 Quantifying importance of bilateral gait assessment

Bilateral gait assessment is not common in F&A studies with unoperated / unaffected side largely been ignored and or presumed normal. An investigation looking at bilateral performance found that unilateral ankle surgeries can, in fact, have an equally detrimental effect on the contralateral side. For example, surgical comparison found that TAR and TTCA surgeries resulted insignificantly better gait symmetry than AA. In fact, even preoperative AOA patients showed better bilateral gait mechanics than the AA. Results showed the importance of bilateral gait assessment.

7.1.3 Comparing subjective and modern objective gait assessment methods

Studies repeatedly showed the importance of using AGA over subjective assessment methods, with subjective assessment notably exaggerating how well a patient is performing. F&A surgery outcomes were compared against each other based on clinical scores as well as gait assessment. While clinical scores showed all surgeries to result in a similar functional status, significant differences were to be seen in objective assessment.

7.1.4 Development of a robust gait assessment score

A predictive and robust model for quantifying patient functionality was developed using principle component analysis (PCA) for parameter reduction and optimization and a general scoring system for individual parameter performance relative to controls. The base model was developed using the AGA results for the reduced parameter set with a final score being given corresponding to the total individual parameter points scaled to a maximum score of 100. Final scores coincide with all previous comparative studies throughout the thesis suggesting that such a multivariate assessment of a specific set of gait parameters is not only feasible, but provides a more accurate description of a patient's functionality than subjective scores.

7.2 Clinical significance

The work presented here is an important step towards promoting the use of AGA in clinical practice. Hence, a validated AGA was successfully applied for assessment of selected foot and ankle pathologies and their treatments. Furthermore, the development of the gait assessment score simultaneously transforms AGA to a simplified and to a more accurate assessment tool. It has, therefore, the potential to be used more easily in clinical practice and for research purposes. It not only permits the objective evaluation of F&A pathologies and the efficacy of their treatment but also has the potential to be used for optimization of early rehabilitation and, therefore, to prevent the development of adapted and or compensatory gait patterns.

Moreover, in context with the cost effectiveness and availability, the gait score could also be utilized to assess the quality of the existing F&A clinical scores and check their robustness and accuracy and find the most accurate functional score available. The score could also be employed in developing a new subjective functional score for F&A pathologies which could correlate 1 to 1 with the gait score.

7.3 Perspectives

Further research is now required to test the reliability and the robustness of the developed gait score. Studies involving larger population sizes, various and also less severe F&A pathologies should be conducted. Applicability of the score to optimize early rehabilitation protocols after F&A surgery should also be studied.

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Appendix 1: Gait Assessment Protocol

Protocol for multi-segment foot and lower limb biomechanics measurement using wearable systems

Protocol is developed by Hossein Rouhani as part of his doctoral research at LMAM-EPFL

Slight modifications were made in the protocol with respect to the current study

Devices:

1- Inertial sensors (Physilog)
2- Pressure insoles (Pedar, Novel)

Measurement for each foot takes around 1 hour.

Sensor installation :

1- « Vicon » double-faced tapes are used for attaching inertial sensors on the skin.
2- Make sure all systems are fully charged and ready to use. Note that, Physilog's charge is usually sufficient for up to 3 to 4 measurements, however, Pedar system needs to be charged after 1 or 2 measurements. Pedar also provides two batteries so rotation of battery after every 2 measurements could be helpful and prevent unexpected data loss.
3- Develop the folder for each measurement and name it with the initials of name, furthermore gather information regarding the height, weight, age, shoe size and pathology (pre-op, post-op, follow-up period, pathology side and other pathologies).
4- Difference size of Pedar insoles are available, so try different sizes for the participants and make a tradeoff between suitable length and width of the insoles. Take a note of the chosen insole size.

5- Attach the insoles to the corresponding custom made sandals. Use the rolled wide tapes for this purpose; put the tapes in the way to avoid sliding of the insoles both in antero-posterior and medio-lateral directions. Insole must be placed well in the sandals from all directions.

6- For the inertial sensors, attach the double-side tapes on the opposite face of the label-face of the sensor. Place the inertial sensors on the skin in the way that their cables are facing the proximal/ upward directions. Place the sensors as close as possible in the anatomical planes.

7- Inertial sensor placements :

  i- Master A: proximal phalanx of the first ray (phalanges), on the dorsal aspect, between the first interphalangeal and metatarsophalangeal (MPJ1) joints.

  ii- Master B: between the bases of the first and the second metatarsals, dorsal aspect.

  iii- Slave A: The posterior aspect of the great tuberosity of the calcaneus, just below the end point of the Achilles tendon.

iv- Slave B: The medial aspect of the tibia, close to the ankle joint, on the bony surface, away from the tibialis anterior muscle.

v- Master Third: The medial aspect the contra-lateral tibia, close to the ankle joint, on the bony surface, away from the tibialis anterior muscle.

8- Reinforce the inertial sensor over the skin by additional medical micropore tape. For Master A sensor, role the tape around the hallux to secure the sensor position.

9- To enhance contact between the foot and the insole, role two series of tapes around the foot and shoe.

10- Neatly collect the free cables of inertial sensors on each foot and secure them with a Velcro band around ankle, leaving enough length for free ankle and MPJ flexion-extension.

11- Connect the Pedar-box to the insoles using the Pedar-cable, such that the foot figure on the Pedar cables must face outward and visible from both sides.

12- Fasten the Velcro of the sandals with the Velcro band around ankle to secure the insole cables.

13- Lastly, fasten Velcro bands around both shanks and thighs to hold all the cables. Provide sufficient cable length for the knee flexion.

Data-logger (boxes) connections:

1- Insert the SD cards inside the Physilogs. Do not forget to empty the SD cards before inserting.

2- Connect the synchronization cables: the red points on the cables and the Physilogs (master and slave) must always align with each other. The connecting cable for the master Physilog is signed which makes it easy to differ between the slave and master connecting cables. While for the Pedar there is an optic connector which must be inserted in the « synch in » (trigger in) port of the Pedar-box. Connect the Pedar box to its battery using its cable.

3- Fasten the belt, to hold the two Physilogs, Pedar box and battery, around participant’s waist comfortably tight enough.

4- Make sure the Pedar cable does not bend during, both, sensor installation and measurement. Place the Pedar-box in the belt in the lateral side of body. Place it a bit in posterior side in order to avoid its antenna being hidden by participant’s arm.

5- Ask the participant to walk around a little to see if the worn system is comfortable, especially if the belt is too tight or a cable stretches during gait.

Pedar software setup:

1- Connect the hard-key and the Bluetooth dangle to the laptop’s USB ports.

2- Open the Pedar software. Give a name to the files : « initials-participant's name followed by the number given to the participant»

3- Choose the insole type in 100 Hz

4- In the Pedar software follow:

   a. Data acquisition> test connection: check if the connection is with BT, write a number of those in the list into the box and click on "test connection". Confirm that « connection is ok ».

   b. Data acquisition>Mode> set it to "Online+flash"

   c. Expert setting>edit insole configuration>insole type> set the cut-off to 1kPa

   d. Expert setting> Expert setting>edit insole configuration>>sync setup : trigger-input=> each picture

   e. Data acquisition>load configuration> load insole types to flash

   f. Data acquisition>Measurement with mask> delete all masks, select Right or Left insole, choose all elements on this insole, load this mask, set the frequency to 200Hz, ask the subject to unload the left and then the right insole

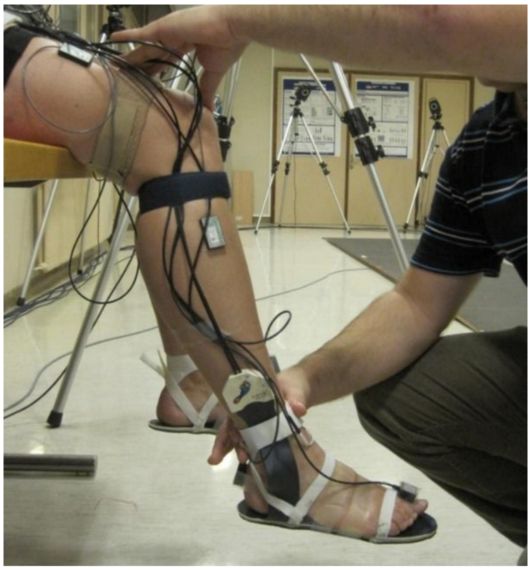
Measurement protocol:

Functional calibration of the inertial sensors:

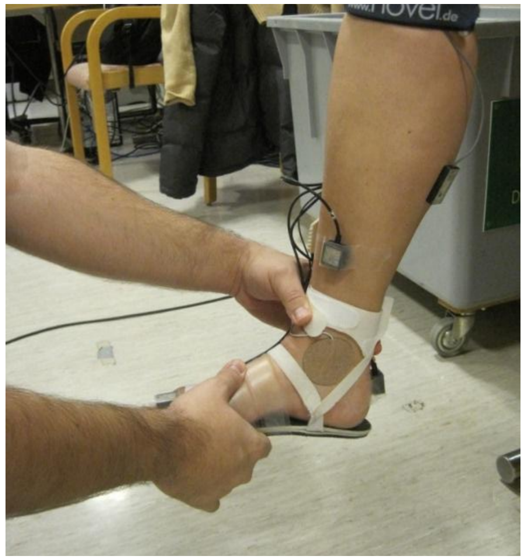
1- First step, ask participant to stand still for at least 10 sec. Describe them to stand straight with natural distance and opening angle between the feet. Press the master Physilog button to turn ON the system and then press again to turn OFF after around 10 sec. (the program uses the median posture).

2- In general, for each Physilog recording, press start of the master Physilog while asking the subject to stand motionless then waist to see twice the synchronized blinking of the LED on the Physilogs. Then the subject can move (or walk). After finishing the movements press the Physilog button to stop recording. Wait to see that all LEDs turn off. Then you may start another recording.

3- Second step, ask participant to sit on a table, ask them to hold his ankle and foot joints fixed while the knee is not blocked. Also ask them not to perform any active movement. Then the examiner will turn ON the Physilog and perform passive flexion-extension at the knee joint for 20 times, with rather fast pace. Turn OFF the Physilog as soon as the test finish.



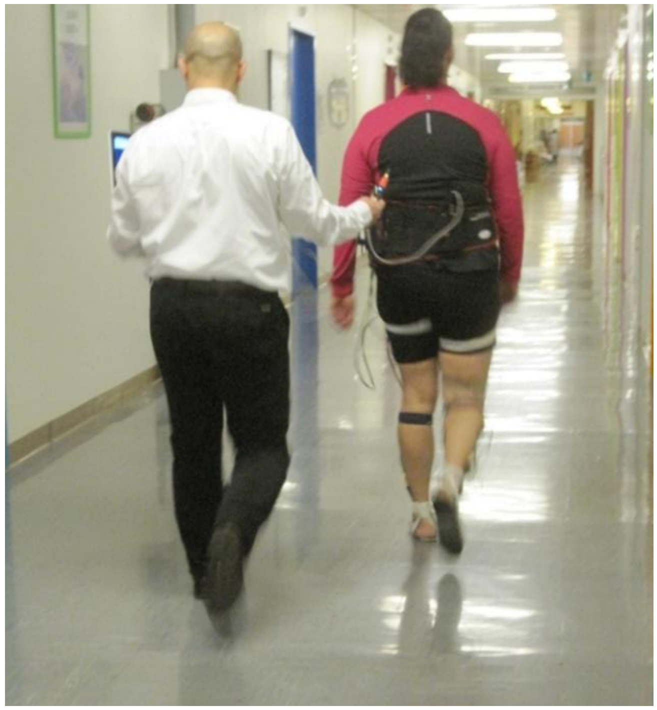
4- Third step, while the participant still sit on the table, ask to relax the ankle but with no active ankle motion. Turn ON the Physilog and perform ankle flexion-extension 20 times in a relatively faster pace after which turn OFF the Physilog.



Corridor gait measurement:

5- Final step, click on the red button on the Pedar software interface. Bring the participant to the corridor and ask them to stand straight facing the direction of the corridor. Explain the participant to walk in a natural way along the corridor (50m) with their preferred walking speed. Ask to walk on a straight line as much as possible without losing the natural gait. Describe them NOT TO TURN as soon as they reach to the end of the corridor and instead ask them to stand still as soon as they stop walking.

6- Press the Master Physilog button, wait to see the synchronized blinking of the Physilogs and Pedar functioning synchronized to Physilogs. Meanwhile subjects MUST stand still for at least 1 sec before starting the gait. After fulfilling all these conditions, ask the participant to walk to the end of the corridor. Follow the participant with the laptop.



7- Stop the Master Physilog at the end of the corridor after participant stops walking. Then, press (||) button in the Pedar software to record the Pedar data.

Data saving:

Create four folders: M (master), S (slave), and P (Pedar) in each subfolder.

1- Cut-paste the BIN files from the Master and Slave SD cards to the corresponding folders.

2- Copy the ASCII files in "P" folder of the participant.

Appendix II: Clinical Scores (AOFAS, FAAM, EQ 5D)

AOFAS Score Cheville - Arrière-pied (100 Points Total)

Douleur (40 points)

□ 40 Aucune

□ 30 Faible, occasionnelle

□ 20 Modérée, quotidienne

□ 0 Sévère, Presque toujours présente

Fonction (50 points)

Limitation des activités, moyens auxiliaires requis

□ 10 Pas de limitation, pas de moyens auxiliaires

□ 7 Pas de limitation des activités quotidiennes, limitations des activités récréatives, pas de moyens auxiliaires requis

□ 4 Limitation des activités quotidiennes et récréatives, canne basse

□ 0 Limitation sévère des activités quotidiennes et récréatives, déambulateur, béquilles, fauteuil roulant

Périmètre de marche maximal

□ 5 Plus que 600 mètres

□ 4 400-600 mètres

□ 2 100-300 mètres

□ 0 Moins de 100 mètres

Surfaces de marche

□ 5 Aucune difficulté quelle que soit la surface

□ 3 Quelques difficultés en terrain inégal, dans les escaliers, en pente, sur les échelles

□ 0 Difficultés sévères en terrain inégal, dans les escaliers, en pente, sur les échelles

Anomalies de la marche

- ☐ 8 Aucunes, discrètes
- ☐ 4 Evidentes
- ☐ 0 Marqueés

Mobilité sagittale (flexion-extension)

- ☐ 8 Normale ou faible restriction (30° ou plus)
- ☐ 4 Restriction modérée (15°-29°)
- ☐ 0 Restriction sévère (moins de 15°)

Mobilité de l'arrière-pied *(inversion-éversion)*

- ☐ 6 Normale ou faible restriction (75-10% de la normale)
- ☐ 3 Restriction modérée (25-74% de la normale)
- ☐ 0 Restriction sévère (moins de 25% de la normale)

Laxité de la cheville – arrière-pied (antéro postérieure et varus-valgus)

- ☐ 8 Stable
- ☐ 0 Vraiment instable

Alignement (10 points)

- ☐ 10 Bon, pied plantigrade, cheville – arrière-pied bien alignés
- ☐ 5 Altéré, pied plantigrade, quelques degrés de désaxation de la cheville – arrière-pied, pas de symptômes
- ☐ 0 Mauvais, pied non plantigrade défaut d'axe sévère et symptomatique

Foot and Ankle Ability Measure (FAAM)

Evaluation des capacités fonctionnelles du pied et de la cheville

Merci de répondre à **chaque question** en donnant la réponse qui décrit le mieux votre état au cours de la semaine passée (une seule réponse par question).

Si l'activité en question est limitée par autre chose que votre pied ou votre cheville, notez non applicable (N/A).

	Pas de difficulté	Légère difficulté	Difficulté modérée	Difficulté sévère	Incapable de le faire	N/A
Se tenir debout	□	□	□	□	□	□
Marcher sur un terrain régulier	□	□	□	□	□	□
Marcher pied nu sur un terrain régulier	□	□	□	□	□	□
Monter une pente	□	□	□	□	□	□
Descendre une pente	□	□	□	□	□	□
Monter les escaliers	□	□	□	□	□	□
Descendre les escaliers	□	□	□	□	□	□
Marcher sur un terrain irrégulier	□	□	□	□	□	□

Monter et descendre d'un trottoir	☐	☐	☐	☐	☐	☐
S'accroupir	☐	☐	☐	☐	☐	☐
Se mettre sur la pointe des pieds	☐	☐	☐	☐	☐	☐
Faire les premiers pas (le matin au réveil / après une position assise prolongée)	☐	☐	☐	☐	☐	☐
Marcher 5 minutes ou moins	☐	☐	☐	☐	☐	☐
Marcher environ 10 minutes	☐	☐	☐	☐	☐	☐
Marcher 15 minutes ou plus	☐	☐	☐	☐	☐	☐

En raison de **votre pied et de votre cheville**, quel est le niveau de difficulté pour faire:

	Pas de difficulté	Légère difficulté	Difficulté modérée	Difficulté importante	Incapable de le faire	N/A
Les tâches ménagères	□	□	□	□	□	□
Les activités de la vie quotidienne	□	□	□	□	□	□
Les soins personnels	□	□	□	□	□	□
Un travail léger à modéré (se tenir debout, marcher)	□	□	□	□	□	□
Un travail lourd (pousser/ tirer, grimper, porter)	□	□	□	□	□	□
Les activités de loisirs	□	□	□	□	□	□

A combien estimez-vous votre niveau actuel de fonctionnement dans les activités habituelles de votre vie quotidienne de 0 à 100, 100 étant votre niveau de fonctionnement avant votre problème de pied ou de cheville et 0 étant l’incapacité à faire la moindre de vos activités quotidiennes habituelles ?

□□□.0 %

Questionnaire EQ-5D

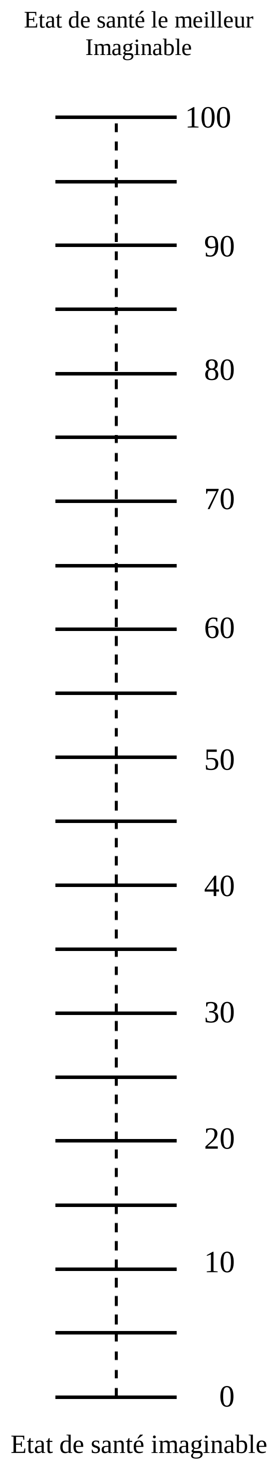
Veuillez indiquer, pour chacune des rubriques suivantes, l'affirmation qui décrit le mieux votre état de santé aujourd'hui, en cochant la case appropriée :

Mobilité :	
Je n'ai aucun problème pour me déplacer à pied	❑
J'ai des problèmes pour me déplacer à pied	❑
Je suis obligé (e) de rester alité(e)	❑
Autonomie de la personne :	
Je n'ai aucun problème pour prendre soin de moi	❑
J'ai des problèmes pour me laver ou m'habiller tout(e) seul(e)	❑
Je suis incapable de me laver ou de m'habiller tout(e) seul(e)	❑
Activités courantes : *(exemple : travail, études, travaux domestiques, activités familiales ou loisirs)*	
Je n'ai aucun problème pour accomplir mes activités courantes	❑
J'ai des problèmes pour accomplir mes activités courantes	❑
Je suis incapable d'accomplir mes activités courantes	❑
Douleurs/gêne :	
Je n'ai ni douleurs, ni gêne	❑
J'ai des douleurs ou une gêne modérée	❑
J'ai des douleurs ou une gêne extrême	❑
Anxiété/dépression :	
Je ne suis ni anxieux (se), ni déprimé(e)	❑
Je suis modérément anxieux (se) ou déprimé(e)	❑
Je suis extrêmement anxieux (se) ou déprimé(e)	❑

Cette section permet de nous renseigner sur votre état actuel (EQ-5D) :

Pour vous aider à indiquer dans quelle mesure tel ou tel état de santé est bon ou mauvais, nous avons tracé une échelle graduée (comme celle d'un thermomètre) sur laquelle 100 correspond au meilleur état de santé que vous puissiez imaginer et 0 au pire état de santé que vous puissiez imaginer.

Nous aimerions que vous indiquiez sur cette échelle où vous situez votre état de santé aujourd'hui. Pour cela, veuillez tracer une ligne allant de l'encadré ci-dessous à l'endroit qui, sur l'échelle, correspond à votre état de santé aujourd'hui.



Appendix III: The Gait Score

Scoring instructions

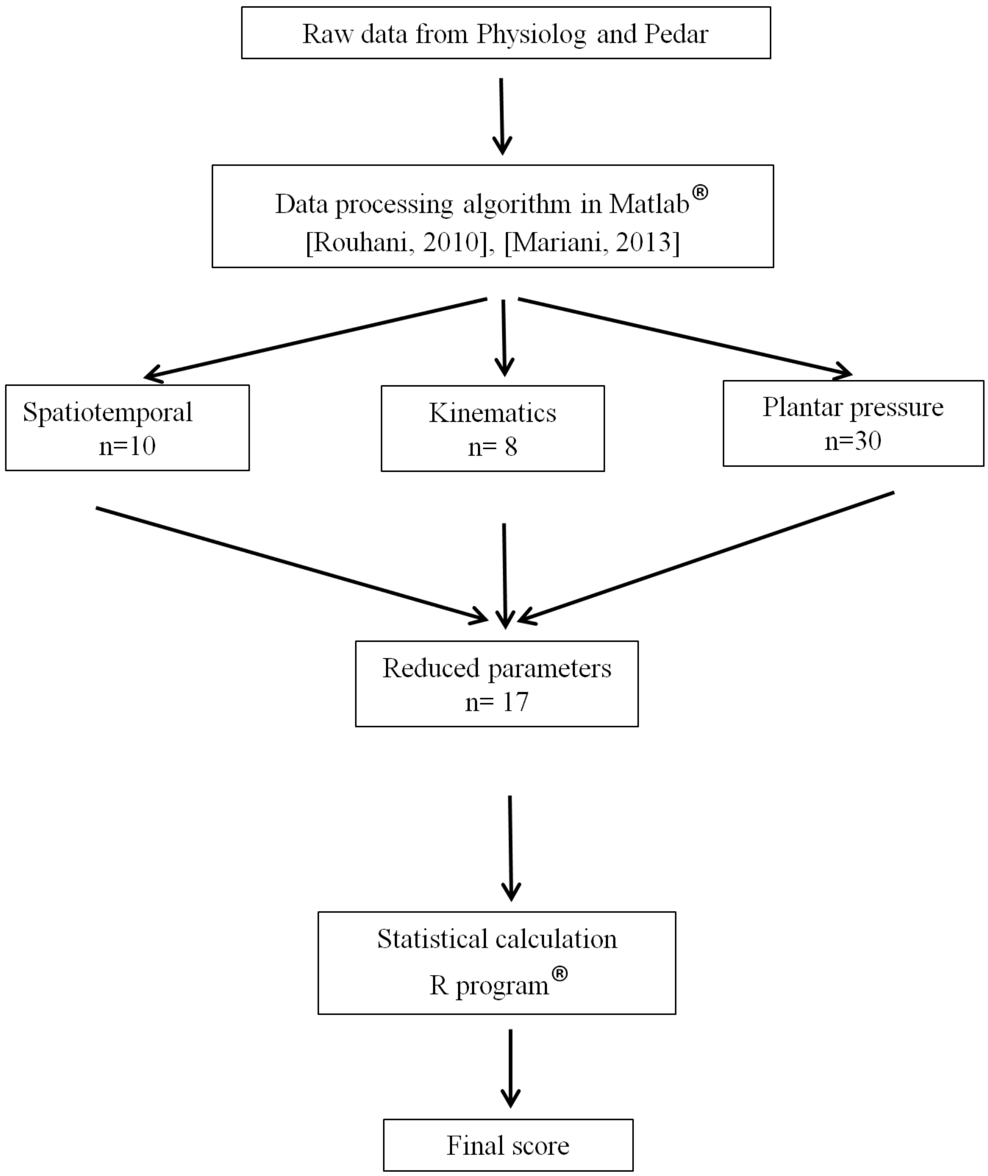


Figure 1a: Flowchart representing process of development of gait score from the raw gait data.

Scoring results in our population

Table 1 (a-d) shows gait score for AOA, AA, TAR and TTCA patients with bilateral outcome.

AOA	group	Cad	Spd	PSS	TOP	MTP-s	MT-s	Ank-s	Ank-c	TcHL	fHM	pHM	TcML	TcFC	TcTF	fTF	pTF	fTS	Total	Final Score
1	Aff	1	0	1	1	0	2	1	1	1	0	0	1	0	0	0	0	1	10	80
2	Aff	3	3	3	3	3	1	2	1	2	1	1	1	1	2	1	1	1	30	41
3	Aff	0	0	1	1	0	1	0	1	2	1	1	1	1	2	1	1	1	15	71
4	Aff	1	3	3	3	2	2	1	1	1	1	0	1	0	1	1	1	1	23	55
5	Aff	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	19	63
6	Aff	2	2	2	1	1	1	0	0	2	1	1	1	1	1	1	1	1	19	63
7	Aff	0	1	0	1	1	1	1	1	0	1	0	1	1	1	1	1	1	13	75
8	Aff	1	2	2	1	1	1	1	1	0	1	1	0	1	2	1	1	1	18	65
9	Aff	2	3	3	2	2	2	2	0	1	1	1	1	0	1	1	1	0	23	55
10	Aff	1	1	2	1	1	1	1	0	0	0	0	0	0	0	0	0	1	9	82
1	Unaff	1	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	10	80
2	Unaff	2	3	3	3	2	1	1	1	2	1	1	0	1	1	1	1	0	24	53
3	Unaff	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	14	73
4	Unaff	1	3	1	2	2	1	1	1	3	1	1	1	1	1	1	1	0	22	57
5	Unaff	1	1	0	0	0	0	0	0	1	1	1	2	1	0	1	1	0	10	80
6	Unaff	1	1	2	1	1	0	0	0	1	1	1	0	0	1	1	1	1	13	75
7	Unaff	0	0	1	1	1	1	0	0	0	1	0	2	1	2	0	1	0	11	78
8	Unaff	1	2	1	1	1	1	0	1	1	0	0	1	1	0	1	1	1	14	73
9	Unaff	2	3	3	2	1	1	1	1	1	1	1	2	1	2	1	0	0	23	55
10	Unaff	1	1	1	1	1	1	0	1	3	1	1	1	1	1	1	1	0	17	67

Table 1a: Gait score for AOA patients.

AA	group	Cad	Spd	PSS	TOP	MTP-s	MT-s	Ank-s	Ank-c	TcHL	fHM	pHM	TcML	TcFC	TcTF	fTF	pTF	fTS	Total	Final Score
1	Op	0	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	10	80
2	Op	1	1	1	1	1	1	1	2	0	1	1	0	0	1	0	0	0	12	76
3	Op	1	0	1	1	2	2	1	1	1	0	1	0	0	1	1	1	0	14	73
4	Op	2	2	2	1	2	2	1	0	0	1	1	0	0	1	1	1	0	17	67
5	Op	1	1	1	2	2	2	1	1	1	0	0	1	1	1	1	1	1	18	65
6	Op	0	0	1	1	1	2	1	1	1	1	1	0	1	2	1	1	1	16	69
7	Op	1	2	1	2	2	2	1	1	1	0	0	1	1	1	1	1	1	19	63
8	Op	1	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	23	55
9	Op	2	2	2	2	2	2	1	1	2	1	1	1	1	1	1	0	1	23	55
10	Op	2	2	3	2	3	2	1	1	1	0	0	1	0	1	1	1	0	21	59
11	Op	1	1	2	1	1	2	1	1	1	1	1	0	0	1	1	1	1	17	67
1	Unop	0	0	0	0	1	1	0	0	3	1	1	3	2	1	0	0	1	14	73
2	Unop	0	1	1	0	0	0	0	0	3	0	0	2	2	2	0	1	1	13	75
3	Unop	1	0	1	0	1	0	0	1	3	1	1	3	2	1	1	1	0	17	67
4	Unop	1	1	1	1	1	1	0	1	2	0	0	3	1	1	1	0	0	15	71
5	Unop	1	1	0	0	0	0	0	0	3	1	1	2	2	0	0	0	0	11	78
6	Unop	0	0	0	0	1	0	0	0	2	0	0	1	2	1	1	1	1	10	80
7	Unop	1	1	1	0	1	1	0	0	3	1	1	2	2	1	0	0	0	15	71
8	Unop	2	2	1	1	1	1	0	0	3	1	1	2	2	1	0	0	1	19	63
9	Unop	1	2	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	17	67
10	Unop	1	1	1	0	1	1	1	0	0	0	0	1	1	2	0	1	1	12	76
11	Unop	1	1	1	1	0	1	0	0	1	1	1	2	1	1	1	1	1	15	71

Table1b: Gait score for AA patients.

TAR	group	Cad	Spd	PSS	TOP	MTP-s	MT-s	Ank-s	Ank-c	TcHL	fHM	pHM	TcML	TcFC	TcTF	fTF	pTF	fTS	Total	Final Score
1	Op	0	0	1	0	0	1	1	0	0	1	0	1	0	0	1	1	1	8	84
2	Op	1	2	2	1	1	1	1	1	1	1	1	1	1	0	1	1	1	18	65
3	Op	1	1	2	0	1	1	0	1	0	1	1	1	0	1	1	1	0	13	75
4	Op	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	14	73
5	Op	1	1	1	1	1	2	1	0	1	1	1	1	0	1	1	0	0	14	73
6	Op	0	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	1	12	76
7	Op	0	0	1	1	0	1	1	1	0	0	0	1	0	0	1	1	0	8	84
8	Op	1	1	0	1	0	1	1	1	0	0	0	1	1	0	0	1	1	10	80
9	Op	1	2	2	3	2	2	1	2	1	0	0	1	1	0	0	0	0	18	65
10	Op	0	1	1	1	0	1	1	0	1	2	1	0	1	1	1	1	1	14	73
11	Op	0	0	1	1	2	1	0	0	0	0	1	0	0	0	0	1	0	7	86
12	Op	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	12	76
13	Op	0	0	0	1	1	1	0	1	2	1	1	1	0	1	1	1	1	13	75
14	Op	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15	71
15	Op	1	1	2	1	1	1	1	1	1	0	0	1	1	0	1	1	0	14	73
16	Op	2	3	3	2	2	2	1	1	2	0	0	1	1	1	1	1	1	24	53
1	Unop	0	0	1	0	1	1	0	0	1	1	0	1	1	1	0	0	1	9	82
2	Unop	1	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	8	84
3	Unop	1	1	1	0	0	0	0	0	1	0	1	1	1	1	0	1	1	10	80
4	Unop	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	0	5	90
5	Unop	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	15	71
6	Unop	0	1	1	0	0	0	0	1	1	1	1	1	0	1	1	1	1	11	78
7	Unop	0	0	0	0	1	1	1	0	1	0	0	1	1	0	0	0	0	6	88
8	Unop	1	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	5	90
9	Unop	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0	11	78
10	Unop	0	1	0	0	0	1	0	1	1	0	0	0	1	1	1	0	0	7	86
11	Unop	1	0	0	0	0	1	0	1	1	0	0	1	0	1	1	0	1	8	84
12	Unop	0	0	1	1	1	1	1	0	1	0	0	1	0	0	1	0	0	8	84
13	Unop	0	0	0	0	1	1	1	0	3	0	0	1	1	1	0	0	0	9	82
14	Unop	1	1	2	2	0	2	0	0	1	0	0	1	0	1	0	1	0	12	76
15	Unop	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0	14	73
16	Unop	2	3	1	1	2	1	0	0	2	0	0	2	0	1	0	0	0	15	71

Table1c: Gait score for TAR patients.

TTCA	group	Cad	Spd	PSS	TOP	MTP-s	MT-s	Ank-s	Ank-c	TcHL	fHM	pHM	TcML	TcFC	TcTF	fTF	pTF	fTS	Total	Final Score
1	Op	1	1	0	1	1	1	1	1	1	1	1	0	1	0	1	1	0	13	75
2	Op	2	2	2	2	1	2	1	2	2	0	0	1	0	0	1	1	0	19	63
3	Op	1	2	1	2	1	1	1	1	2	0	1	1	0	0	0	0	1	15	71
4	Op	1	1	1	1	1	1	1	1	1	0	1	2	0	0	1	0	1	14	73
5	Op	1	2	2	1	1	1	1	1	2	1	1	1	1	1	0	1	0	18	65
6	Op	1	2	3	2	1	1	1	1	1	1	1	1	1	2	1	1	0	21	59
7	Op	0	0	0	1	1	1	1	1	1	0	0	1	0	1	1	1	0	10	80
8	Op	0	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	0	12	76
9	Op	2	3	3	3	1	1	1	1	1	0	1	1	0	1	0	0	0	19	63
10	Op	2	3	3	2	1	1	1	1	3	0	1	1	1	1	1	1	1	24	53
11	Op	0	1	1	1	2	1	1	1	1	1	1	1	0	0	1	0	0	13	75
1	Unop	0	1	1	1	1	1	1	1	1	0	0	2	1	1	0	0	1	13	75
2	Unop	2	2	3	2	1	1	1	0	2	0	0	1	0	1	0	1	1	18	65
3	Unop	1	2	1	1	1	1	0	0	2	1	1	2	0	2	1	1	1	18	65
4	Unop	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	7	86
5	Unop	1	1	2	1	1	1	0	0	3	1	1	1	0	2	1	1	1	18	65
6	Unop	0	1	0	2	1	1	1	1	2	1	0	1	0	1	0	0	0	12	76
7	Unop	0	0	0	0	1	0	0	0	1	1	1	1	0	3	1	1	0	10	80
8	Unop	0	1	1	1	0	0	0	0	0	1	1	2	0	0	0	0	0	7	86
9	Unop	2	3	2	2	1	1	0	1	2	0	0	1	1	1	0	0	0	17	67
10	Unop	2	2	2	1	2	1	0	0	1	0	0	1	0	1	0	0	0	13	75
11	Unop	0	0	1	1	1	1	0	1	1	0	0	1	0	0	1	1	0	9	82

Table1d: Gait score for TTCA patients.

Legends for the final score displayed in table 1

Cadence (steps/min) -Cad

Speed (m/s)-Spd

Toe-off pitch angle (°) - TOP

Peak swing speed (°/s) - PSS

TO-FF Sagittal plane ROM- MTP-s

FF-HF Sagittal plane ROM- MT-s

FF-SH Sagittal plane ROM- Ank-s

FF-SH Coronal plane ROM- Ank-c

Hindfoot lateral total contact duration (% St) - TcHL

Midfoot lateral total contact duration (% St) - TcML

Forefoot central total contact duration (% St) - TcFC

First toe total contact duration (% St) - TcTF

Hindfoot medial maximum force (BW %) - fHM

Hindfoot medial maximum pressure (kPa) - pHM

Second toe maximum force (BW %) - fTS

First toe maximum force (BW %) - fTF

First toe maximum pressure (BW %) - pTF

Appendix IV: Thesis related publications

Pilot Study

1. **Chopra S**., Moerenhout K. & Crevoisier X. ***"Characterization of gait in female patients with moderate to severe hallux valgus deformity"***, Clin Biomech, 30**,** 629-35 (2015).

2. **Chopra S**., Moerenhout K. & Crevoisier X. ***"Subjective vs Objective Assessment in Early Clinical Outcome of Modified Lapidus Procedure for Hallux Valgus Deformity"***, Clin Biomech, 2015, In Press. DOI: http://dx.doi.org/10.1016/j.clinbiomech.2015.11.012.

Surgical Comparative Studies

3. **Chopra S**., Rouhani H., Assal M., Aminian K. & Crevoisier X. ***"Outcome of unilateral ankle arthrodesis and total ankle replacement in terms of bilateral gait mechanics"***, J Orthop Res, 32**,** 377-84 (2014).

4. **Chopra S**., Pichonnaz M. J. & Crevoisier X. ***"Biomechanical Outcome of Tibiotalocalcaneal Arthrodesis and Ankle Arthrodesis"***, submitted in Journal of Biomechanics, December 2015.

5. **Chopra S**., Pichonnaz M. J. & Crevoisier X. ***"Bilateral Gait Mechanics in Unilateral End-stage Ankle Osteoarthrosis"***, submitted to Journal of Applied Biomechanics, November 2015.

Objective Method Optimization

6. **Chopra S**., Rouhani H., Moerenhout K., Favre J., Aminian K., Crevoisier X. ***"Outcome of ankle arthrodesis and total ankle replacement for ankle arthrosis in terms of gait variability",*** Journal of Biomedical Engineering and Informatics, 2**,** 3-38 (2015).

7. **Chopra S**., Favre J. & Crevoisier X. ***"Qualitative Analysis of Foot Intersegment Coordination in the Sagittal Plane Following Surgery for End-stage Ankle Osteoarthrosis",*** submitted to Journal of Orthopedic Research, December 2015.

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Characterization of gait in female patients with moderate to severe hallux valgus deformity

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ABSTRACT

Background: Hallux valgus is one of the most common forefoot problems in females. Studies have looked at gait alterations due to hallux valgus deformity, assessing temporal, kinematic or plantar pressure parameters individually. The present study, however, aims to assess all listed parameters at once and to isolate the most clinically relevant gait parameters for moderate to severe hallux valgus deformity with the intent of improving post-operative patient prognosis and rehabilitation.

Methods: The study included 26 feet with moderate to severe hallux valgus deformity and 30 feet with no sign of hallux valgus in female participants. Initially, weight bearing radiographs and foot and ankle clinical scores were assessed. Gait assessment was then performed utilizing pressure insoles (PEDAR®) and inertial sensors (Physilog®) and the two groups were compared using a non-parametric statistical hypothesis test (Wilcoxon rank sum, $P < 0.05$). Furthermore, forward stepwise regression was used to reduce the number of gait parameters to the most clinically relevant and correlation of these parameters was assessed with the clinical score.

Findings: Overall, the results showed clear deterioration in several gait parameters in the hallux valgus group compared to controls and 9 gait parameters (effect size between 1.03 and 1.76) were successfully isolated to best describe the altered gait in hallux valgus deformity ($r^2 = 0.71$) as well as showed good correlation with clinical scores.

Interpretation: Our results, and nine listed parameters, could serve as benchmark for characterization of hallux valgus and objective evaluation of treatment efficacy.

1. Introduction

Hallux valgus (HV) deformity is an outward lateral angulation of the great toe and is most commonly found in female patients in clinical practice (Nix et al., 2010; Roddy et al., 2008). The deformity is progressive in nature, and can eventually become debilitating, compromising activities of daily living of the patients. At an advanced stage, the deformity is known to cause pathologic gait deviation due to continual pain and discomfort. Studies have even shown a link between severe HV and impaired balance/frequent incidence of falls in elderly patients (Menz and Lord, 2001, 2005).

There are a wide variety of surgical interventions available for the correction of HV, based on the type and severity of the deformity, yielding good to excellent outcomes depending on the profile of the patients and on the outcome measures applied (Lin and Bustillo, 2007). A number of studies have assessed the outcome of these surgical procedures, most of which are based on questionnaires and radiographic evaluation (Dennis and Das De, 2011; Garrido et al., 2008; Kopp et al., 2005) with relatively few on plantar loading (Bryant et al., 2005; Martinez-Nova et al., 2011). There are also few studies which have assessed gait deviation in HV patients (Canseco et al., 2010; Deschamps et al., 2010; Galica et al., 2013; Mickle et al., 2011; Waldecker, 2002; Wen et al., 2012). Based on the results of a systematic review by Nix et al. (2013) a number of fundamental limitations exist in these studies and there is no determinable agreement in the results. This would suggest that information regarding gait characterization in HV deformity is yet to be fully explored.

With the advancement of technology and further development in wearable motion sensors and pressure insoles (Lambrecht and Kirsch, 2014; Razak et al., 2012), it is likely that gait assessment will be included as part of diagnostic and outcome assessment in the foreseeable future. Studies have already isolated gait parameters which define gait deviations (Chopra et al., 2014; Mariani et al., 2012, 2013; Mickle et al., 2011; Rouhani et al., 2011a; Taranto et al., 2007; Yavuz et al., 2009), however not all of those parameters are clinically meaningful for specific deformities. It is therefore important that we not only characterize gait deviations in HV patients but also simplify the procedure by reducing the number of assessed parameters to the most clinically relevant. The gait parameter which displays significant alteration due to the extent of the HV deformity and positively correlates to the clinical scores,

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with a potential to accurately assess the prognosis post operatively will be counted among the clinically relevant gait parameters.

This study aims to investigate the gait characteristics in patients with moderate to severe HV deformity by assessing spatiotemporal, kinematic and plantar pressure parameters, as well as their variability. Furthermore, the study aims to simplify gait assessment by isolating the most clinically relevant parameters in defining gait alterations in HV patients.

2. Methods

2.1. Participants

Twenty six female feet with moderate to severe HV deformity and thirty healthy female feet were assessed. Inclusion criteria for the HV group include radiographic results of hallux valgus angle (HVA) and M1–M2 intermetatarsal angle (IMA) between 20–40° and 14–20° respectively, and presence of significant pain due to HV. In the case group, patients with HV present in both feet had each measured as an independent observation. The exclusion criteria included the presence of any other pathology of the foot and ankle and or previous surgeries or trauma of the lower limbs/other conditions which may affect their gait. All the participants gave their informed consent and approval of the ethics commission of the University hospital was obtained.

2.2. Clinical assessment

Commonly used foot and ankle questionnaires, including Foot and Ankle Ability Measure (FAAM) (Borloz et al., 2011) and American Orthopaedic Foot and Ankle Society (AOFAS) (Hunt and Hurwit, 2013) forefoot score, were administered to evaluate the preoperative functional status of patients with the HV deformity.

Radiographic assessment was performed by a single independent observer and illustrated the IMA, HVA and distal metatarsal articular angle (DMAA) (Fig. 1).

Fig. 1. Radiographic measurements in weight bearing position representing M1–M2 intermetatarsal angle (IMA), hallux valgus angle (HVA) and distal metatarsal articular angle (DMAA).

2.3. Gait assessment

Gait assessment was performed using ambulatory pressure insoles (Pedar-X®, Novel, Germany) and five 3-D inertial sensors, connected to two portable data-loggers (Physilog®, BioAGM, CH) (Rouhani et al., 2011b, 2012). The sensors were placed at the medial aspect of both tibias, and on the tested foot, to the posterior aspect of the great tuberosity of the calcaneus between the base of the first and second metatarsals, and on the dorsal aspect of the proximal phalanx of the first toe. The insoles were available in 4 different sizes along with the custom made sandals, can be found in Fig. 2.

To carry out the gait assessment, each participant was asked to walk twice, back and forth, along a 50 m long hospital corridor at their normal walking speed. The plantar pressure data were collected, from the 99 cells of the Pedar-X® insoles, at the sampling rate of 200 Hz. The stance time of the gait cycles for each trial was identified using sum of the pressure over loaded elements of the insole (Rouhani et al., 2011b). The kinematic data were collected, from the Physilog® system, during the 100% stance phase of the gait cycle at a rate of 200 Hz (Rouhani et al., 2012). For kinematic assessment, foot and ankle complex is divided into four joint segments (shank, hindfoot, forefoot and toes) and the joint angles were calculated based on the proximal and distal segments (Rouhani et al., 2012). To obtain repeatable joint angles consistently among subjects, the sensor signals and subsequent joint angles were expressed relative to the foot and shank's anatomical frames, instead of the inertial sensors' technical frames (Rouhani et al., 2012). A detailed description of the validated measurement protocol can be seen in previous publications (Rouhani et al., 2011b, 2012). The first and last three cycles of each trial were discarded to eliminate the wayward effects during initiation and termination of walking. The average of all remaining gait cycles was then taken for each trial. Spatiotemporal, kinematic (joint angles) and plantar pressure parameters were assessed for all gait cycles of each walking trial of 50 m. From an average of 35 to 40 gait cycles per trial for each participant spatiotemporal parameters were assessed, including: stance phase of the gait cycle time (GCT%); cadence, double support time (GCT%), inner-stance events (loading, foot-flat and push-off phase (stance phase %)); stride length (m), speed (m/s), peak swing speed (°/s), toe off pitch angle (°) and heel strike pitch angle (°). Three dimensional joint angles including dorsi-plantar flexion, inversion–eversion, internal–external rotation were assessed in their respective plane of movement i.e. sagittal, coronal and transverse plane during 100% of the stance phase for both the 1st metatarsophalangeal joint (MTP1) and the total foot, based on the forefoot–toe and shank–forefoot segments respectively. Plantar pressure

Fig. 2. Sensor placement for the tested foot.

parameters were assessed at 10 different anatomical sub-regions — hind-foot lateral and medial ((HL), (HM)), mid-foot lateral and medial ((ML), (MM)), fore-foot lateral, central and medial ((FL), (FC, (FM)) and toes divided into first toe (TF), second toe (TS) and lateral toes (TT) (Rouhani et al., 2011b). The parameters assessed included; total contact duration (% stance time), maximum pressure (kPa) and maximum vertical force (% body weight). Furthermore, gait variability (GV) for all gait parameters were assessed for each participant from the two groups.

2.4. Statistical analysis

Results were analyzed using MATLAB version 2011a (The MathWorks Inc. ®) and compared the average of each gait parameter over a full gait cycle for both patients and controls. For each parameter, mean, standard deviation (STD) and coefficient of variation ($CV\% = 100 \times STD / mean$) was calculated. The CV% represented the gait variability for each parameter. The comparison between HV patients and the controls were performed using the non-parametric Wilcoxon rank-sum test with statistical significance set at ($P < 0.05$). The resultant gait parameters, showing a significant difference when compared to the control group, were then filtered via forward stepwise regression to form a model containing only the most clinically relevant in describing gait deviations due to severe HV deformity. The coefficient of determination, indicating the refined model's accuracy, was calculated via the adjusted r^2 method to establish the model's degree of freedom in the model and the correlation between the filtered gait parameters and FAAM and AOFAS scores was investigated using Spearman's correlation coefficient. The effect size of these 9 parameters was calculated using the Cohen's d formula.

3. Results

3.1. Clinical assessment

Demographics of the study population and clinical score results are presented in Table 1. As expected, both scores reported a significantly reduced functional status when compared with the controls. The radiographic results of the HV patients presented mean IMA of 15.5° (13–20), an HVA of 31.3° (22–39) and DMAA of 9.7° (0–16).

3.2. Gait assessment

3.2.1. Spatiotemporal parameters of gait and their variability

Table 2 shows the spatiotemporal parameter results along with the stride to stride gait variability. The HV group showed a significantly reduced ($P < 0.05$) cadence, push-off, speed, maximum swing speed and toe-off pitch angle while significant increase in the foot-flat and double support, when compared with the control group. The inner stance distribution of both groups is shown in Fig. 3. As shown, comparing the stride to stride gait variability of each gait cycle in the HV group to the control population showed significant reduction only in foot-flat parameter.

3.2.2. Kinematic parameters and variability

The kinematic parameters and their variability for both the MTP1 joint and total foot were assessed in all 3 planes (Table 3) and a comparative analysis between HV group and controls was carried out for kinematic parameters (Fig. 4). At MTP1, in all three planes of movement (sagittal, coronal and transverse) a significant reduction in the range of mobility was reported throughout the stance phase. On the other hand, at the total foot, a significant reduction in movement was noted in the sagittal plane. Kinematic variability between the two groups showed significant difference only in the sagittal plane movement at the MTP1 joint.

3.2.3. Plantar pressure parameters and variability

The plantar pressure outcome of the 10 aforementioned foot subregions was assessed for HV group and controls. In hindfoot and midfoot, lateral and medial subregions, significantly increased total contact duration was reported while it is found to be reduced significantly at the first toe region in HV group compared to controls. Maximum vertical force was found to be significantly increased in midfoot lateral and decreased in first toe region. Finally, maximum pressure was found to be significantly high at the midfoot lateral and lateral toe regions and significantly low at the first toe region (Table 4). A comparison of the standardized mean difference of total contact duration, maximum vertical force and maximum pressure between controls and HV group for the defined subregions is shown in Fig. 5. The variability in plantar pressure parameters was found to be significantly different compared with the control group in total contact duration, maximum vertical force or maximum pressure in most sub-regions with the exception of midfoot lateral, forefoot lateral and lateral toes (Table 4). Furthermore, a significant difference in total contact duration variability was only observed in hind foot lateral and first toe regions, while a

Table 1
Demographics & clinical scores outcome, results in mean (STD).

Physical characteristic	HV	Control
Age (years)	53.69 (10.57)*	49.8 (6.45)
BMI (kg/m2)	23.3 (3.9)	22.5 (3.7)
FAAM (%)	68.69 (18.5) *	100 (0)
AOFAS	46.4 (11)*	100 (0)

* $P < 0.05$.

Table 2
Spatiotemporal parameters of gait with their variability (GV) in HV and control groups, results in mean (STD).

Gait parameters	HV (STP)	Control (STP)	HV (GV (%))	Control (GV (%))
Cadence (steps/min)	105.47 (12.88)*	122.46 (8.85)	3.37 (1.33)	2.98 (0.79)
Stance (GCT%)	58.81 (1.74)	58.30 (1.79)	3.18 (1.64)	2.79 (1.17)
Loading (St%)	10.41 (1.99)	12.05 (3.55)	13.45 (6.63)	10.64 (3.82)
Foot-flat (St%)	59.84 (6.24)*	50.64 (6.85)	4.64 (2.3)*	6.16 (2.27)
Push-off (St%)	29.75 (5.11)*	37.29 (5.14)	7.43 (2.95)	7.63 (2.61)
DS (GCT%)	24.19 (6.01)*	20.33 (3.5)	10.1 (7.2)	12.5 (5.8)
Stride length (m)	1.23 (0.17)	1.32 (0.125)	9.11 (4.23)	9.90 (3.47)
Speed (m/s)	1.11 (0.25)*	1.36 (0.18)	10.42 (3.66)	11.12 (2.87)
PSS (°/s)	369.60 (56.19)*	438.49 (44.36)	9.06 (3.51)	9.29 (3.89)
TOP (°)	−68.24 (8.06)*	−80.07 (4.9)	9.12 (5.03)	9.64 (5.54)
HSP (°)	19.10 (3.6)	20.49 (4.35)	14.69 (5.4)	14.57 (4.11)

DS: double support, PSS: peak swing speed of shank, TOP: toe-off pitch angle, HSP: heel-strike pitch angle, GCT: gait cycle time, St%: stance %.
* $P < 0.05$.

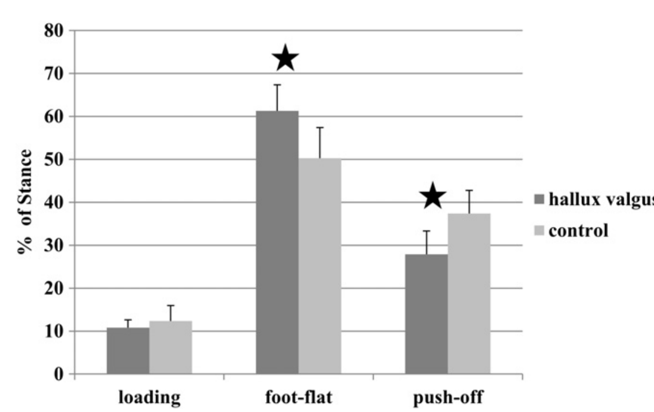

Fig. 3. Inner stance events (loading, foot-flat and push-off) in HV and controls. ★ represents significant difference as compared to control ($P < 0.05$).

Table 3
Kinematic results and their variability (GV) in HV and control groups, results in mean (STD).

Joint	Planes	HV Joint angle (deg)	Control Joint angle (deg)	HV (GV (%))	Control (GV (%))
MTP1	Sagittal	34.8 (8.3)*	40 (5.1)	6.3 (4.2)*	4.3 (1.6)
	Coronal	10.97 (3.4)*	12.7 (3.9)	15.3 (6.3)	15.5 (7.6)
	Transverse	7.9 (1.7)*	9.1 (3.7)	15.3 (6.3)	15.5 (7.6)
Total foot	Sagittal	27.3 (5.0)*	31.0 (7.7)	8.9 (4.5)	8.1 (3.9)
	Coronal	16.9 (4.3)	16.1 (4.2)	14.4 (7.4)	16.2 (5.7)
	Transverse	14.3 (6.6)	13.5 (4.4)	14.4 (7.4)	16.2 (5.7)

* $P < 0.05$.

similar comparison in maximum vertical force variability showed significant difference in 6 out of 10 sub-regions; hindfoot lateral and medial, forefoot central and medial, second toe and first toe. Variability in maximum pressure was found to be significantly different in midfoot medial and first toe regions. Significant increase in gait variability was observed in all three plantar pressure parameters at the first toe region.

3.2.4. Determination of clinically relevant gait parameters and their correlation with clinical scores

Out of 47 parameters including 11 spatiotemporal, 6 kinematic and 30 plantar pressure parameters (3 parameters in 10 subregions each), 9 gait parameters were isolated to be the most clinically relevant and best describe the altered gait in HV deformity. This predictive model was constructed using the forward stepwise regression method from the selected parameters which were found to have a maximum adjusted r^2 (coefficient of determination) of 71. These parameters include cadence, speed, foot-flat phase, push-off phase, peak swing speed, toe-off pitch angle, MTP1 motion around sagittal plane, total contact duration at hind foot (lateral and medial) and peak vertical force at the first toe. The effect sizes of these parameters were 1.53, 1.06, 1.38, 1.45, 1.31, 1.76, 1.03, 1.55 and 1.5 respectively. Finally correlation between the constructed model and the clinical scores was assessed, to which AOFAS forefoot score showed a correlation of 0.47 while FAAM outcome score showed a correlation of 0.78.

4. Discussion

This study aimed to characterize gait in moderate to severe hallux valgus deformity with the intent of simplifying gait assessment by reducing the number of assessed parameters to those most clinically relevant. Comparing HV patients to a control group, the results showed significant alterations in a number of gait parameters. Further, nine gait parameters including spatiotemporal, kinematic and plantar pressure parameters were successfully isolated which are all clinically relevant and can characterize gait in HV deformity. These parameters also showed a fair to good correlation with AOFAS and FAAM scores, respectively and hence can represent both functional and biomechanical aspect of outcome assessment when used in clinical practice.

Spatiotemporal results of this study showed a visible deterioration in several parameters in contrast to previous studies (Canseco et al., 2010; Deschamps et al., 2010; Mickle et al., 2011). Interestingly, a longer foot-flat phase along with a weaker push-off in HV deformity was observed (Fig. 3) which could be a sign of affected second and third rockers of the foot during the stance phase of the gait cycle. The altered third rockers of foot at the MTP1, at least in severe HV deformity, would affect weight transfer, progressively affecting a patients' walking momentum and would result in increased energy expenditure during walking. This might not be a very demanding situation for young adults but for elderly population this could have a considerable effect on their quality of life. The unstable weight transfer, increased energy consumption in walking along with several other age related problems can make the situation more complicated leading to a significant reduction in physical activity levels in elderly, which itself is a problem.

Kinematic results showed significantly reduced movement at MTP1 (Table 3) which corresponds to two available studies on kinematics in HV deformity (Canseco et al., 2010; Deschamps et al., 2010). However, of these studies, one assessed only sagittal plane mobility (Deschamps et al., 2010) and the other did not adequately define the severity of HV in their study population (Canseco et al., 2010), questioning their

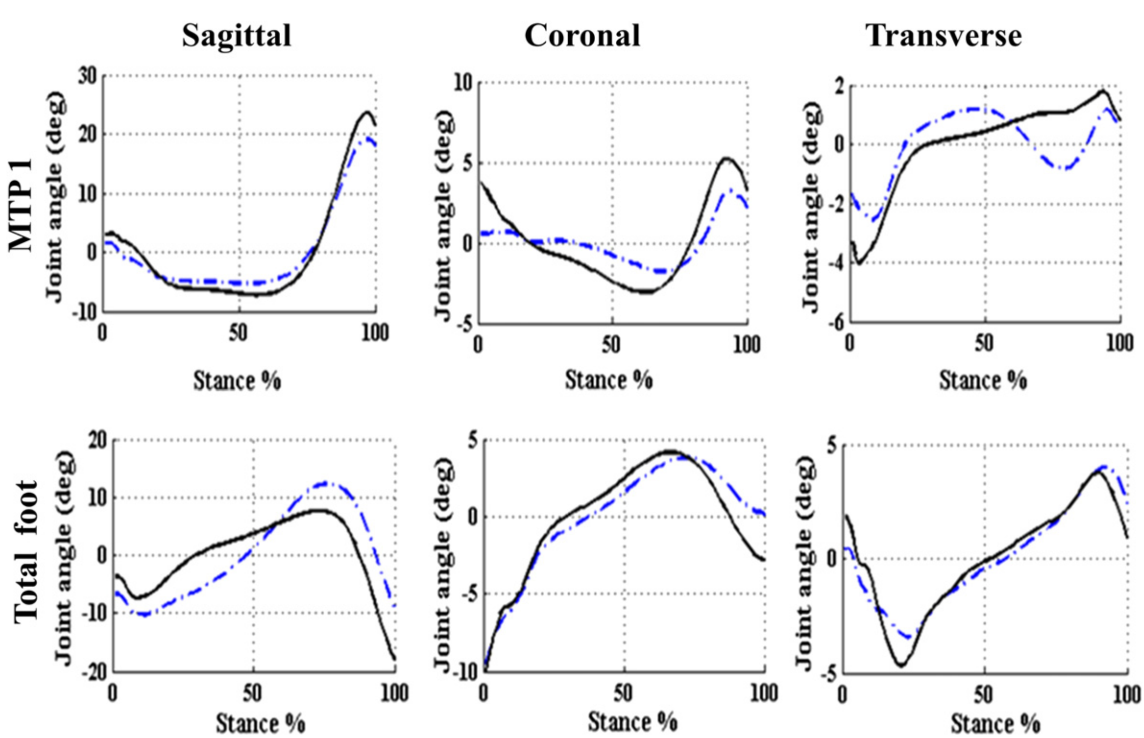

Fig. 4. Kinematic curves in three planes at MTP1 and total foot. Solid line represents controls and dash-dot line represents HV group.

Table 4
Plantar pressure parameters (PPP) and their variability (GV) in HV and control groups in 10 sub-regions of foot, results are given in mean (STD).

Foot sub-regions	Gait parameters	HV (PPP)	Control (PPP)	HV (GV (%))	Control (GV (%))
HL	Tc	57.7 (8.2)*	46.6 (6.4)	10.6 (4.8)*	7.3 (2.6)
	Max F	27.6 (8.9)	31.3 (10.2)	14.2 (6.7)*	9.6 (5.5)
	Max P	95.8 (28.8)	102.8 (28.3)	99.5 (21.3)	101.7 (26.7)
HM	Tc	62.5 (10.2)*	49 (6.4)	9.3 (4.7)	7.9 (2.7)
	Max F	38.8 (12.3)	39 (8.6)	12.6 (8.5)*	8.2 (3.8)
	Max P	119.2 (41.5)	131.5 (30.1)	92.2 (23.4)	80.4 (14.6)
ML	Tc	52.5 (15.79)*	36.2 (14.8)	17.8 (16.4)	23.7 (18.3)
	Max F	12.5 (7.8)*	7.7 (5.1)	31.2 (17)	40.1 (35.7)
	Max P	33.5 (17)*	21.6 (9.8)	133.4 (54.5)	154.5 (36.8)
MM	Tc	37.4 (17.5)*	20.6 (11.7)	24.4 (15.4)	21.56 (16.1)
	Max F	5.4 (4.7)	3.1 (2.8)	51.1 (51.9)	67.6 (64.7)
	Max P	14.5 (9.5)	10.3 (5.3)	202.3 (33.3)*	216.8 (50.6)
FL	Tc	78.9 (13)	77.1 (10.9)	8.9 (7.4)	6.1 (6.8)
	Max F	35.2 (13.1)	31.1 (6.3)	18.1 (9.8)	16.8 (6.8)
	Max P	117.8 (40.8)	111.7 (27.8)	73.6 (15.9)	82.2 (14.6)
FC	Tc	70.1 (69.7)	69.7 (12.1)	11.2 (8.1)	6.9 (4.4)
	Max F	27.8 (10.9)	28.8 (5.4)	17.4 (19.1)*	6.6 (4.4)
	Max P	124.4 (49.3)	129.6 (24.1)	89.8 (19.3)	84.8 (13.7)
FM	Tc	47 (15)	46.6 (15.3)	29.1 (12.3)	21.9 (12.4)
	Max F	14 (7.2)	14.2 (5.8)	42.3 (22.6)*	33 (21.1)
	Max P	58.7 (27.6)	60.8 (25)	125.7 (30)	121.5 (17.1)
TT	Tc	24.3 (11.9)*	16.6 (9.2)	31.3 (21.2)	34.1 (18.3)
	Max F	5.6 (4.1)	3.8 (3)	43 (37.4)	43.4 (28.3)
	Max P	24.4 (14.8)*	16.3 (8.9)	150.1 (43.9)	181.4 (51.8)
TS	Tc	25.4 (10.4)	25.1 (12.6)	25.4 (19.8)	16.9 (12.4)
	Max F	5.8 (3.3)	5.7 (3.6)	30.5 (18.2)*	21.5 (16.7)
	Max P	46.2 (23.8)	41.2 (16.7)	95.3 (42.9)	113 (35.4)
TF	Tc	34.2 (12.5)	37.2 (10.9)	32 (18.1)*	15.3 (7.9)
	Max F	10.2 (8.7)*	16.5 (8.3)	25.9 (9.3)*	21.5 (16.2)
	Max P	55.9 (32.7)*	83.3 (28.1)	152.4 (41.6)*	108.1 (17.6)

Tc: total contact duration (stance %), Max F: maximum vertical force (BW%), Max P: maximum pressure (kPa); foot subregions — HL: hindfoot lateral, HM: hindfoot medial, ML: midfoot lateral, MM: midfoot medial, FL: forefoot lateral, FC: forefoot central, FM: forefoot medial, TT: 3rd to 5th toes, TS: second toe, TF: first toe.
* $P < 0.05$.

validity. The present study has none of these shortcomings as we included clinically defined moderate to severe HV patient population and movement at all three planes were assessed. Our results suggested that the reduced mobility at MTP1 at the terminal stance could justify the reduced toe-off pitch angle and peak swing speed along with the incomplete push-off phase observed in our patient group. For the total foot, overall reduced movement along the sagittal plane was reported in HV group in comparison with the controls, although at the terminal stance increased mobility was reported when compared to controls this could be due to the increased compensatory movement at the forefoot for the reduced movement along the sagittal plane at the hallux. Due to the limited availability of literature related to the joint mobility in HV deformity it is hard to draw conclusions as to significance of these findings.

Plantar pressure results found various similarities and contradictions to previous studies. In the toe region, this study found a significantly reduced peak pressure at the hallux and an increased peak pressure on the 3rd–5th toes in HV group similar to Galica et al. (2013). This is, however, in stark contrast to a few studies who either found no significant differences in hallux pressure (Mickle et al., 2011) or reported an increased peak pressure at the hallux region (Bryant et al., 2005; Martinez-Nova et al., 2010). Furthermore, looking at the forefoot regions, under the metatarsal heads, no significant difference was found in any peak pressure compared to controls, similar to some studies (Galica et al., 2013; Martinez-Nova et al., 2010), while others reported contrasting results with an increased peak pressure under the first and second metatarsal heads (Bryant et al., 2000, 2005; Mickle et al., 2011). In the midfoot regions, an increased loading of the midfoot lateral region was also witnessed, while no previous study reported any differences. Finally, our results showed a longer contact duration in the hindfoot and midfoot regions in HV patients, which has not been previously studied in detail. It is clear that discrepancies and contradictions are present in existing gait studies of HV deformity, however, our results were found to be consistent, with regard to maximum force and peak pressure, with the Framingham foot study (Galica et al., 2013), which assessed gait in 1123 feet with HV deformity.

Gait variability describes fluctuation in stride–stride gait parameters (Hausdorff, 2005). It has been found to be positively associated with increased instability and increased risk of fall in several medical conditions, including aging (Arnold et al., 2011; Stergiou and Decker, 2011). Existing studies reported an increased risk of fall in HV patients above 75 years of age with an impaired gait, especially on uneven terrain (Menz and Lord, 2001, 2005). In the elderly population, there could be several medical reasons for an increased risk of fall along with the general deterioration due to aging, reduction in physical activity levels, reduced speed of walking and increased gait variability. It is known that gait variability in spatiotemporal and kinematic gait parameters are more valuable compared to plantar pressure in relation to the risk of fall (Callisaya et al., 2010; Hamacher et al., 2011). It is not known, however, if there is a relation between increased gait variability due to HV deformity and an increased risk of falling. Based on our results, a significant increase in variability in plantar pressure parameters and sagittal plane movement at hallux was reported in HV group in comparison with the controls, this is likely due to the constant pain in moderate to severe stage of the deformity. In theory, HV could be a contributing factor towards the increased risk of falling in older elderly with moderate to severe HV, in contrast to their younger counterparts. Our findings suggest that gait variability does not seem like a meaningful assessment parameter regarding moderate to severe HV deformity as it can be affected by several other health and age related factors.

Lastly, the study managed to successfully isolate the nine gait parameters most clinically relevant in characterizing gait variations in HV patients. The nine parameters include cadence, speed, foot-flat, push-off, peak swing speed, toe-off pitch angle, MTP1 sagittal plane movement, total contact duration at hind foot and peak vertical force at the first toe. These nine gait parameters also showed good correlation

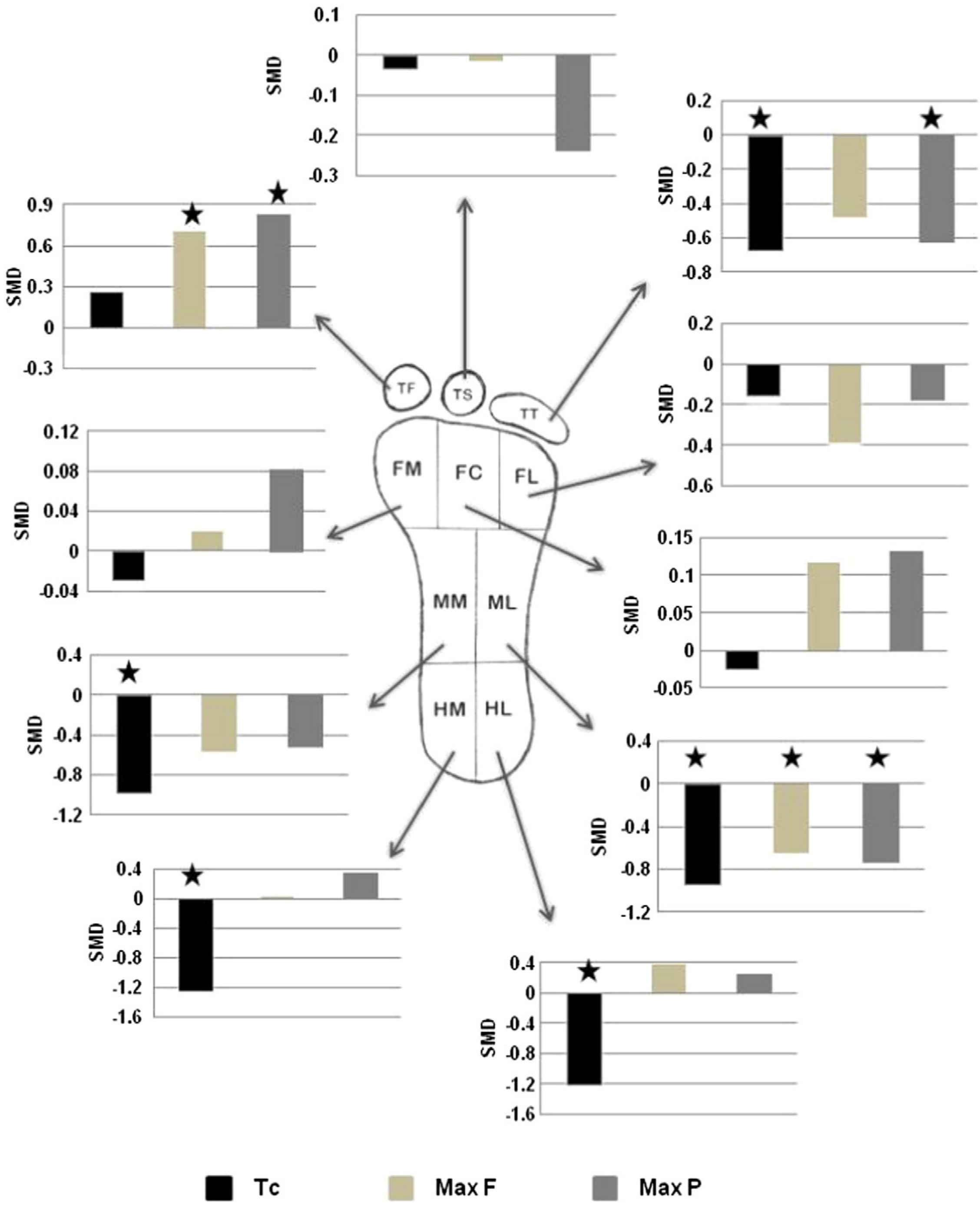

Fig. 5. Standardized mean difference (SMD) between control and HV group for plantar pressure parameters at 10 subregions of foot. Negative graph represents higher values in HV groups as compared to controls, ★ represents ($P < 0.05$).

with the clinical scores which shows the clinical significance of these parameters in terms of functional outcome. It is also therefore assumed that these parameters alone can adequately describe abnormal gait mechanics in HV patients. For example, a gait with slow speed and low cadence is a sign of low activity level and can fairly describe the existence of apprehensive and or pain. Long foot-flat and short push-off duration, along with a slow peak-swing speed, describes altered toe propulsion during the terminal stance and early swing phase. Reduced toe-off pitch angle and MTP1 sagittal movement can describe the reduced mobility of the hallux and toes. The longer contact duration at the hind foot, explains the compensation due to the weak propulsion during weight transfer. Finally, weak vertical force at the first toe could help in understanding the partial loading of the hallux due to pain. Postoperatively, it would be the aim of the rehabilitation to bring these parameters back in-line with an accepted standard for a good biomechanical prognosis.

This study does have a limitation in that the control population is significantly ($P < 0.05$) younger compared to the hallux valgus patients. However, the age difference is merely four years on average, and is highly unlikely to have caused a divergent outcome. The BMI of participants in both the groups also falls under the healthy weight, representing a similar general health status. To conclude, this study proposes to simplify gait assessment in clinical practice by utilizing the ambulatory gait assessment method and by reducing the number of assessed gait parameters to only the nine most clinically relevant. This would ultimately consume less time and make gait assessment in clinical practice feasible. Hence, this paper is an attempt towards simplification of gait assessment for clinical practice.

5. Conclusion

The study successfully isolated nine gait parameters which can best describe the altered gait present in HV patients. The clinical significance of this study is the potential benchmarking in characterizing the severity of HV, the simplification of gait assessment for use in clinical practice and potential contribution to objective evaluation of treatment efficacy and value of rehabilitation programs.

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Subjective versus objective assessment in early clinical outcome of modified Lapidus procedure for hallux valgus deformity

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ABSTRACT

Background: Studies have assessed the outcome of hallux valgus surgeries based on subjective questionnaires, usually the American Orthopaedic Foot and Ankle Society Score, and radiographic results reporting good to excellent outcome at 6–12 months postoperatively. However, contrasting results were reported by gait studies at 12–24 months postoperatively. In a previous study, we found nine gait parameters which can describe the altered gait in hallux valgus deformity. This study aimed, to assess the outcome of modified Lapidus at 6 months postoperatively, using gait assessment method, to determine if the nine specified gait parameters effectively relates with the clinical scores and the radiological results or add information missed by these commonly used clinical assessments.

Method: We assessed 21 participants including 11 controls and 10 patients with moderate to severe hallux valgus deformity. The patient group was followed 6 months postoperatively. The ambulatory gait assessment was performed utilizing pressure insoles and inertial sensors. Clinical assessment includes foot and ankle questionnaires along with radiographic results. Comparison was made using non parametric tests, $P < 0.05$.

Findings: Altered gait patterns, similar to the preoperative outcome, persisted at 6 months postoperatively when compared to controls. The foot and ankle ability measure score showed an outcome comparable to the gait results. In contrast, the American Orthopaedic Foot and Ankle Society Score and radiographic results showed significant improvement.

Interpretation: Study supports the reliability of nine defined gait parameters in assessing the outcome of hallux valgus surgeries. The existing clinical assessment overestimates the functional outcome at the early postoperative phase.

1. Introduction

Hallux valgus (HV) is one of the most commonly seen orthopedic conditions in clinical practice with an estimated prevalence of 23% to 35.7% (Nix et al., 2010). Several surgical options are available based on the severity of the deformity (Lin and Bustillo, 2007; Robinson and Limbers, 2005). At present, the clinical assessment of the outcome of these surgeries is based on radiographic presentation and subjective questionnaires, mainly the American Orthopaedic Foot and Ankle Society Score (AOFAS) — forefoot (Adam et al., 2011; Coetzee and Wickum, 2004; Dennis and Das De, 2011; Kerr et al., 2010; Kopp et al., 2005; Schuh et al., 2008). However, radiographic images do not take the dynamic loading into account and the reliability of subjective questionnaires has come into question in the last decade (Baumhauer et al., 2006; Button and Pinney, 2004; Guyton, 2001; Parker et al., 2003; SooHoo et al., 2003). According to the cited studies, the AOFAS score has consistently shown an average score of greater than 80 already at 6 months postoperatively (Coetzee and Wickum, 2004; Dennis and Das De, 2011; Kerr et al., 2010; Kopp et al., 2005; Schuh et al., 2008) which could be met with skepticism. Also, regarding HV deformity (Canseco et al., 2010; Chopra et al., 2015; Deschamps et al., 2010; Galica et al., 2013; Wen et al., 2012) and its surgical correction (Bryant et al., 2005; Cancilleri et al., 2008; Dhukaram et al., 2006; Schuh et al., 2010), not many studies have looked upon the complete biomechanical profile of the foot and not much information is available regarding the foot mechanics postoperatively. Furthermore, no clinical study so far has looked upon the outcome of modified Lapidus correction prospectively based on gait assessment.

In recent years, objective gait assessment has left its mark in understanding the biomechanics of the foot and ankle in various foot pathologies and in assessing the functional outcome of the surgeries (Chopra et al., 2014; Khazzam et al., 2007; Turner et al., 2003). Objective gait assessment takes into account dynamic loading, functional progress and

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existing gait impairments. This information could improve rehabilitation with early detection of abnormal gait parameters (Coutts, 1999; Schuh et al., 2009). The new generation gait assessment methods are also portable, affordable and easy to use (Lambrecht and Kirsch, 2014; Razak et al., 2012).

In our previous study (Chopra et al., 2015), nine gait parameters were found which can best describe the altered gait in moderate to severe HV deformity. These nine parameters also showed fair to good correlation with AOFAS and Foot and Ankle Ability Measure (FAAM) score respectively. The aim of the current study was to objectively assess the early outcome of the modified Lapidus procedure for correction of moderate to severe HV deformity at 6 months postoperatively based on subjective questionnaires, radiographic presentations and functional gait assessment. Postoperative follow-up of 6 months was chosen over three months or 12 months because the former is too early for full weight bearing and the latter is long after the peak recovery phase and also because studies have shown good recovery around 6 months postoperatively for HV surgery (Kerr et al., 2010; Schuh et al., 2008, 2009). Another important reason behind choosing the 6 months postoperative period is that, by this time physiotherapy sessions are finished and, in general, the compliance to exercise at home has been shown to decline gradually due to several factors including motivation (Campbell et al., 2001) and hence it is a crucial time to assess the prognosis. The working hypothesis of the study is that gait assessment should show comparable results to the other utilized assessment methods.

2. Materials and methods

2.1. Participants

Ten females patients with moderate to severe HV deformity (mean age 51.3 (10.3) years, mean BMI 22.9 (3.2) kg/m^2) and eleven healthy female volunteers with no sign of HV deformity (mean age 50.4 (7.1) years, mean BMI 24.3 (3.8) kg/m^2) were compared. All ten patients were consecutive cases which were listed for modified Lapidus correction. The contralateral sides of most patients also had signs of HV but are asymptomatic. All 10 patients underwent 9 sessions of physical rehabilitation, 1 session per week, at 3 months postoperatively. The patients were followed at 6 months postoperatively to monitor the early recovery. Indications for modified Lapidus procedure included moderate to severe HV with insufficiency of the first ray as expressed by marked transfer metatarsalgia, and/or hypertrophy of the second metatarsal, and/or osteoarthrosis of the second tarso-metatarsal joint. Patients were excluded if they were affected by neurologic or other pathologies of the lower extremities or have had previous HV corrective surgery. The control population included volunteers with no prior history of neurological conditions or other pathologies of the foot and ankle or any previous surgeries or trauma of lower limbs which may affect their gait. All participants gave informed consent. Approval of the ethics commission of the University was obtained.

2.2. Operative procedure

Lapidus procedure was performed as a modification of the original technique (Lapidus, 1934). Patients were placed supine and given a third generation cephalosporin prophylaxis. A 300 mmHg tourniquet was inflated at the thigh. Percutaneous lateral release of the first metatarso-phalangeal joint (MTP1) was performed, longitudinally sectioning the capsule just above the lateral sesamoid while keeping the tendon of the adductor hallucis intact. A medial longitudinal incision was then carried out, the MTP1 was exposed and the dorso-medial pseudo-exostosis was removed from the first metatarsal head. Another more proximal incision was performed dorsally to expose the first tarso-metatarsal joint (TMT1) and the joint between the first cuneiform and the base of the second metatarsal. Articular cartilage was removed from these joints using a sharp raspatorium, and then the surfaces were prepared by multiple drilling and microfractures. The first and second metatarsal (M1/M2) angle was reduced and the TMT1 was stabilized with two 3.5 mm cortical lag screws. A third positioning screw was then inserted from medial to lateral between the bases of the first metatarsal and the second metatarsal (Fig. 1). At this point, if a contact between the first and second toes was still present, a basal medial closing wedge osteotomy of the basis of the first phalanx of the hallux was performed (Akin osteotomy) and stabilized, medially, with a transosseous 1.0 Vicryl suture. The MTP1 capsule was then closed with separate 1.0 Vicryl sutures and the skin incisions were closed with separate 3.0 Vicryl Rapid sutures. The dressing was adapted to gently pull the first toe into varus. On postoperative day one the dressing was changed, a removable short leg cast was adapted, and patients were mobilized in 10 kg partial weight bearing for six weeks, followed by six weeks of progressive weight bearing. The cast was removed at three months and physiotherapy was continued for about two months.

2.3. Clinical assessment

Clinical assessment included subjective questionnaires — AOFAS forefoot score and FAAM — activity of daily living (ADL) score and radiographic findings (antero-posterior and lateral load radiographies). Radiographic assessment was performed by a single independent observer, illustrating the M1/M2 angle, hallux valgus angle (HVA) and distal metatarsal articular angle (DMAA) (Chopra et al., 2015). The ADL sub score of FAAM was utilized instead of total FAAM (ADL + sports), because the sports section of the score was ignored by most of the patients and hence inclusion of total FAAM score could have masked the real outcome. Both clinical and radiographic assessment were performed preoperatively and six months after surgery.

Fig. 1. *Antero-posterior radiographic presentation of modified Lapidus procedure*. After reduction, fixation was achieved using two 3.5 mm lag screws across the first tarso-metatarsal joint and one positioning screw across the bases of the first and second metatarsals.

2.4. Gait assessment

Gait assessment was performed, once for controls and twice for the case group — preoperatively and 6 months post-operatively, using ambulatory pressure insole (Pedar-X®, Novel, Germany) and five inertial sensors, each consisting of 3-D accelerometers and gyroscopes. The system and the assessment protocol had been previously validated and shown high test–retest reliability (Rouhani et al., 2011a, 2012). Sensors were connected to two portable data-loggers (Physilog®, BioAGM, CH) (Rouhani et al., 2012). The sensors were placed at the medial aspect of both tibias, and on the tested foot, to the posterior aspect of the great tuberosity of the calcaneus between the base of the first and second metatarsals, and on the dorsal aspect of the proximal phalanx of the first toe (Chopra et al., 2015). The insoles were available in four different sizes with custom made sandals.

For gait assessment, participants walked along a 50 m long hospital corridor, at their preferred normal walking speed. This procedure was repeated twice for each participant. The gait data were collected at the sampling rate of 200 Hz. The first three and last three cycles of each trial were discarded to negate the wavering effects during the start and end of the walking trials. The average of all remaining gait cycles was taken for each trial. The kinematic data were collected, during the 100% of the gait cycle (Rouhani et al., 2012). Spatiotemporal, kinematic and plantar pressure parameters were assessed for all gait cycles of each trial.

The spatiotemporal parameters included cadence (steps/min), stance and swing phase (gait cycle time % (GCT%)), inner-stance events (loading, foot-flat, and push-off phases) (stance phase %) (Mariani et al., 2013), heel strike pitch angle (°) and toe off pitch angle (°), peak swing speed (°/s), double support time (GCT%), stride length (m) and speed (m/s). Joint range of motion (ROM) was assessed in the sagittal (dorsiflexion/plantarflexion), coronal (inversion/eversion), and transverse (abduction/adduction) planes for the MTP1 joint during 100% of the gait cycle (Rouhani et al., 2011a, 2012). Plantar pressure parameters including total contact duration (% stance time), maximum pressure (kPa) and maximum vertical force (% body weight) were assessed at 10 anatomical sub-regions based on a previously validated protocol (Rouhani et al., 2011b). The anatomical sub-regions of the foot includes: hindfoot (lateral (HL) and medial (HM)); midfoot (lateral (ML) and medial (MM)); forefoot (lateral (FL), central (FC) and medial (FM)); and toes (divided into third to fifth toes (TT), second toe (ST) and first toe/hallux (FT)).

The nine gait parameters identified as the important parameters in characterizing gait in HV deformity in previous study (Chopra et al., 2015), including cadence, speed, foot-flat phase, push-off phase, peak swing speed, toe-off pitch angle, MTP1 motion around sagittal plane, total contact duration at hind foot (lateral and medial) and peak vertical force at the first toe were specifically scrutinized.

2.5. Statistical analysis

Results were analyzed using MATLAB version 2011a (TheMathWorks Inc.®). For each participant, the average of each gait parameter over all gait cycles was calculated. The Shapiro–Wilk test of normality was performed to test if the normal distribution exists in groups for each assessed parameter. Results showed that most gait parameters were not normally distributed among the groups; therefore non parametric tests were used for comparison. The Wilcoxon rank-sum test was used to compare between the case groups and the controls, while preoperative versus postoperative comparison was performed using the Wilcoxon rank-sign tests. The level of significance was set at $P < 0.05$.

3. Results

3.1. Objective gait assessment

Table 1 shows the spatiotemporal parameters of gait in controls, HV (pre-operative) and post modified Lapidus (6 months post-operative) groups. Significant differences were reported between controls and the two case groups in similar parameters including — cadence, foot-flat, push-off, speed, PSS, TOP ($P < 0.05$) (Fig. 2). The postoperative versus preoperative comparison showed significant difference in push-off duration and TOP ($P < 0.05$). MTP1 motion in all three planes is given in Fig. 3. In the sagittal plane, significantly reduced ROM in both HV 33.9° (8.6) ($P = 0.04$) and post modified Lapidus 27.4° (6.3) ($P = 0.0002$) groups was reported in comparison to the healthy controls 33.9° (8.6). Furthermore, in the coronal plane, significantly reduced ROM was reported in HV group 11.2 (2.8) in comparison to controls 15.1 (4) ($P = 0.026$). No difference was reported postoperatively in comparison to the preoperative outcome for MTP1 motion in all three planes. No significant difference in range of movement was observed between the three groups in the coronal and transverse planes.

The plantar pressure parameter results in 10 sub regions of the foot are given in Table 2. For total contact duration parameter, in comparison with the controls, significant difference was reported in HV group at four regions (HL, HM, ML and TT), and for modified Lapidus patients at seven regions (HL, HM, ML, FL, FC, FM and FT). For the preoperative versus postoperative comparison significant difference was reported at five regions (HL, HM, ML, FL and TF). For the maximum vertical force parameter, significant difference was reported between controls and the two case groups around midfoot lateral and hallux regions, but for the postoperative group the significant difference was also reported at forefoot central region. For the preoperative versus postoperative comparison significant difference was reported only at the lateral toes and hallux regions. Finally, for maximum peak pressure parameter, in comparison with the controls, significant difference was seen at hallux, lateral toes and midfoot lateral regions in preoperative group, while in postoperative group significant difference was reported in hallux, forefoot central and midfoot lateral regions. For preoperative versus postoperative comparison significant difference was seen in forefoot central and lateral toe regions for maximum peak pressure. Midfoot lateral is the only foot region where all three parameters were significantly different between the HV group and the controls. Postoperatively, all three plantar pressure parameters at hallux were seen to deteriorate.

The nine gait parameters, known to characterize gait in HV, showed no improvement postoperatively. In fact, six out of the nine parameters were seen to deteriorate further, including toe-off pitch angle, foot-flat phase, push-off phase, maximum force at hallux, total contact duration at the hindfoot and MTP1 movement in the sagittal plane. Hence, based

Table 1
Spatiotemporal parameters of gait, results in mean (SD).

SPT parameters	Control	HV (pre-operative)	Post Lapidus (post-operative)
Cadence	122.46 (8.85)	106.7 (13.6)**	105.5 (11.38)**
Stance (GCT%)	58.30 (1.67)	59.94 (1.9)	59.1 (2.6)
Load (St%)	12.38 (3.6)	10.7 (1.49)	11.49 (2.77)
Foot-flat (St%)	50.64 (7.2)	58.1 (6.6)**	61.86 (6.4)*,**
Push-off (St%)	37.58 (5.2)	31.2 (5.58)**	26.68 (4.6)*,**
DS (GCT%)	21.1 (2.5)	25.9 (6.6)**	25.1 (5.9)**
Stride length (m)	1.3 (0.1)	1.25 (0.17)	1.2 (0.1)
Speed (m/s)	1.3 (0.2)	1.1 (0.3)**	1.07 (0.2)**
PSS (°/s)	443.26 (50.5)	369.5 (57.5)**	364.05 (43.9)**
TOP (°)	−79.4 (5.6)	−69.6 (9.5)**	−61.5 (6.99)*,**
HSP (°)	19.7 (4.98)	19.9 (2.4)	20.8 (3.4)

DS: double support period, PSS: peak swing speed, TOP: toe-off pitch angle, HSP: heel-strike pitch angle.
* Represents ($P < 0.05$) for preoperative vs postoperative comparison.
** Represents ($P < 0.05$) compared to control.

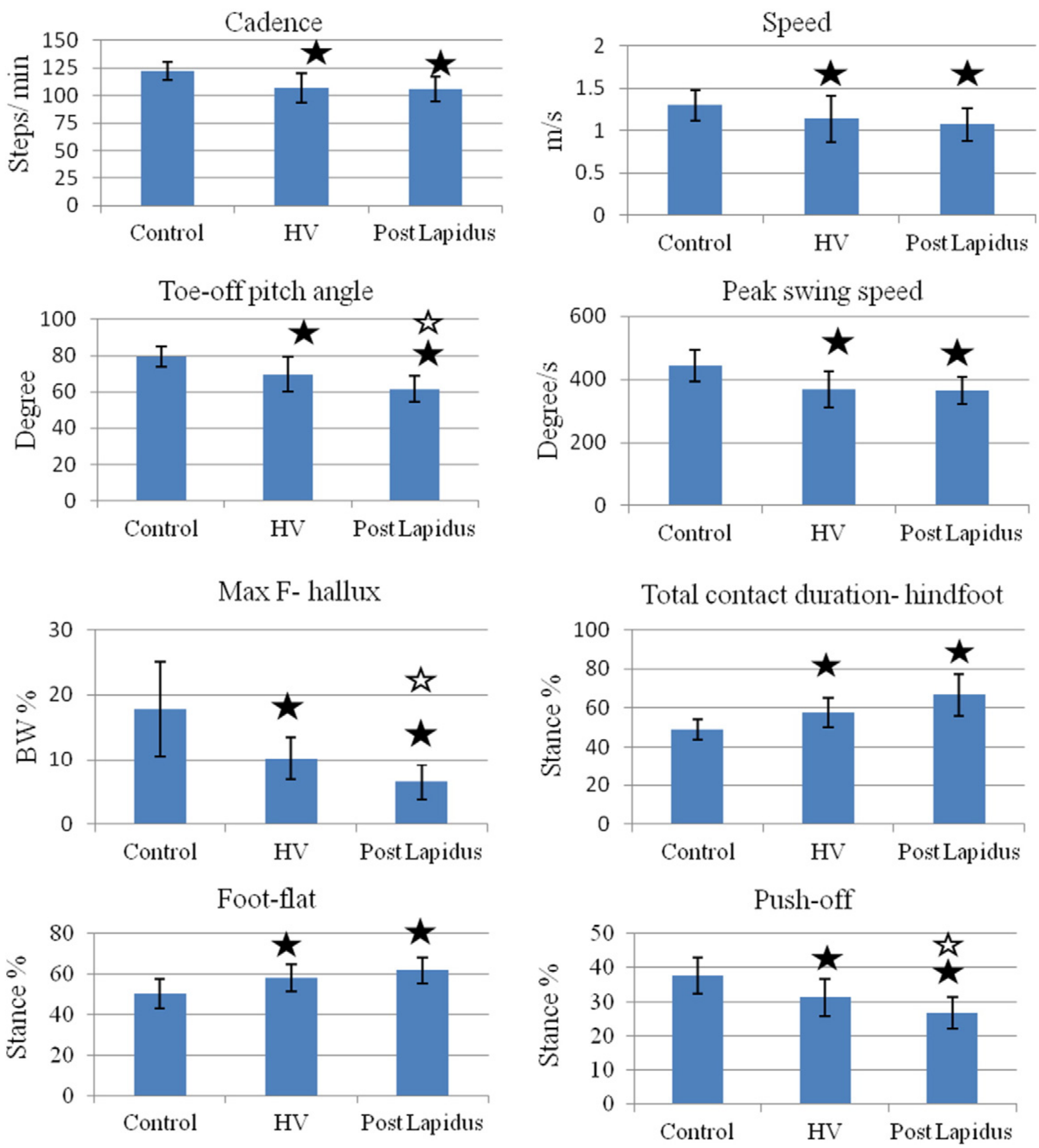

Fig. 2. *Spatiotemporal parameters comparison between the groups*. HV: preoperative hallux valgus, post Lapidus: 6 months postoperatively. ★ represents significant difference compared to control ($P < 0.05$), ☆ represents significant difference compared to preoperative HV.

on the outcome of the nine clinically relevant gait parameters no improvement in gait was reported at 6 months post modified Lapidus in comparison with the preoperative status.

3.2. Subjective and radiographic assessment

The radiographic results preoperatively and 6 months post modified Lapidus procedure are given in Table 3. Results show a significant improvement in the M1/M2 and HVA with no case of non union or delayed union. The AOFAS score also reported significant improvement postoperatively, however moderate restriction in passive ROM both at MTP1 and 1st inter phalangeal joint was reported both preoperatively and 6 months postoperatively with no significant difference. However, the FAAM-ADL score reported a similar outcome as the gait assessment based on the nine clinically relevant gait parameters, showing no improvement in the functional status of the patients.

4. Discussion

The study aimed to assess an early outcome of modified Lapidus procedure for correction of moderate to severe HV deformity based on clinical and functional gait assessment. Furthermore, it aimed to check if the gait assessment method adds clinically relevant information and/or provides similar results to the commonly used assessment methods in clinical practice. The results show that the ambulatory gait assessment method successfully assesses the gait deviation in HV patients as seen in other laboratory based gait studies (Canseco et al., 2010; Deschamps et al., 2010; Galica et al., 2013; Wen et al., 2012). Looking solely at the nine clinically relevant gait parameters for HV deformity, the results showed no improvement in functional outcome of patients at 6 months postoperatively when compared to the preoperative status (Figs. 2 and 3). In contrast, the AOFAS forefoot score and radiographic results showed significant improvement at 6 months postoperatively.

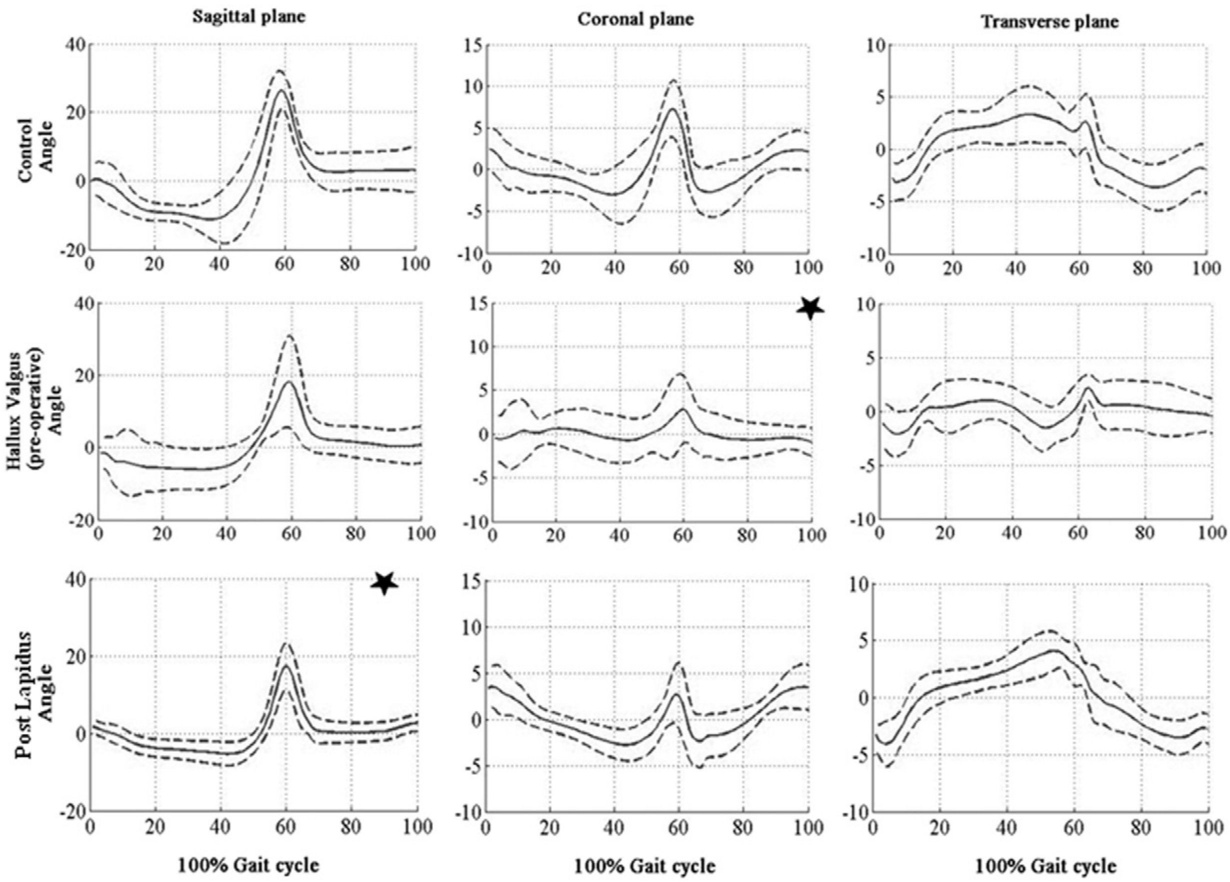

Fig. 3. *First metatarso-phalangeal joint kinematics in the three planes for the three groups during 100% of the gait cycle.* ★ represents significant difference compared to control ($P < 0.05$), no difference reported between preoperative and postoperative outcome.

Several studies have assessed the outcome of various HV correction surgeries based on the commonly used AOFAS forefoot score, and radiographic results (Adam et al., 2011; Coetzee and Wickum, 2004; Dennis and Das De, 2011; Garrido et al., 2008; Kerr et al., 2010; Kopp et al., 2005; Lapidus, 1934; Schuh et al., 2008) and each one of these studies showed an early good to very good outcome similar to the current study. In contrast to this, very few studies have assessed postoperative outcome based on selective gait parameters, mainly the plantar loading, and showed no significant biomechanical improvement 12 or 24 months postoperatively. All these studies have shown an improvement in the AOFAS score and radiographic outcome (Cancilleri et al., 2008; Dhukaram et al., 2006; Saro et al., 2007). The study by Saro et al. (2007) compared the outcome of chevron and Lindgren procedure, based on plantar pressure distribution and reported an increased contact area and peak pressure at hallux 6 months postoperatively, but at 12 month follow-up the results went back to the preoperative level. In contrast to the above study, our study showed reduced plantar loading at hallux 6 months postoperatively. Another study by Schuh et al. (2010) assessed outcome of chevron osteotomy 12 months postoperatively based on plantar loading. The study also provided postoperative physical therapy and gait training for a better rehabilitation of their participants. The outcome of the study showed positive outcome, improved loading at hallux and hence restoration of normal gait (Schuh et al., 2010). Based on the above information, mediocre biomechanical outcomes seem common after HV surgeries even with the radiographic results showing good to excellent anatomic alignment. This undesirably low biomechanical outcome could be perceived as an outcome of incomplete rehabilitation. This proves the importance of physical rehabilitation and early gait assessment for the good functional recovery from HV surgeries. This study also questions the capability of the AOFAS score in assessing the functional status of HV patients postoperatively. However, the AOFAS score is the most commonly used foot and ankle score in clinical practice, but its reliability has been questioned before (Hunt and Hurwit, 2013). Based on our results, the FAAM score showed a comparable outcome with the gait assessment results in comparison to the AOFAS score, which over estimated the outcome. The study suggests the utilization of both objective and subjective assessment for a complete functional assessment.

In clinical practice, so far, gait analysis has been looked upon as a time consuming method of assessment in comparison to physical observation, imaging techniques and health questionnaires. This ideology is strong for smaller joints like foot and ankle in comparison to hip and knee joints. However, with the existing studies, it is clear that the biomechanical prognosis does not reach the expected level after HV surgeries. This is because, so far, no existing method in the clinical practice assesses the biomechanical outcome which could direct towards improvement of biomechanical outcome of the surgeries. But with the simplification of the gait assessment method, as discussed above, and the reduction of the number of assessed gait parameters to the most clinically relevant ones (Chopra et al., 2015), it is an opportunity to promote gait assessment as part of clinical assessment for a better functional outcome of the HV surgeries. This study has few limitations including the small subject size, which could have influenced the results. However, the main aim of the study was not to rate the modified Lapidus procedure, but to compare the outcome of different assessment methods and to see if any similarity exists between the outcome of subjective and objective assessment methods. The nine gait characterizing parameters for HV have already been defined by the previous study with good effect size (Chopra et al., 2015). Hence, the present study, even with the small subject size, showed similar parameters to be clinically relevant

Table 2
Plantar pressure parameters; mean (SD).

Foot sub-regions	Plantar pressure	Control	HV (pre-operative)	Post Lapidus (post-operative)
HL	Tc	46.6 (6.4)	55.7 (8.5)**	66.7 (13.5)*,**
	Max F	31.3 (10.2)	27.4 (6.8)	27.4 (10.6)
	Max P	97.04 (28.7)	91.2 (19.2)	95.4 (35.8)
HM	Tc	49 (6.4)	59.1 (5.9)**	66.5 (7.7)*,**
	Max F	39 (8.6)	41.5 (12.5)	36.6 (12)
	Max P	125.3 (31.3)	120.99 (40.6)	111.8 (42.9)
ML	Tc	36.2 (14.8)	48.8 (17.1)**	65.5 (7.2)*,**
	Max F	7.7 (5.1)	11.8 (8.4)**	13.5 (3.7)**
	Max P	21.6 (9.8)	29.2 (18.5)**	37.2 (9.4)**
MM	Tc	20.6 (11.7)	29.8 (17.6)	37.1 (19.6)**
	Max F	3.7 (2.95)	5.9 (5.7)	3.6 (2)
	Max P	10.3 (5.3)	15.1 (12.1)	12.5 (4.7)
FL	Tc	77.1 (10.9)	79.9 (12)	87.5 (3.3)*,**
	Max F	31.1 (6.3)	36.4 (10.6)	35.5 (14.2)
	Max P	98.4 (23.69)	114.7 (36.7)	113.9 (39.9)
FC	Tc	69.7 (12.1)	70.7 (12)	77.5 (7.7)**
	Max F	29.3 (5.4)	29.1 (10.3)	22.8 (8.8)
	Max P	129.6 (24.1)	131.2 (46.1)	102.3 (25.6)*
FM	Tc	46.6 (15.3)	44.9 (10.1)	62.6 (15.1)**
	Max F	13.67 (5.8)	15.3 (6.4)	13.2 (6.2)
	Max P	60.8 (25)	59.8 (25.6)	56.99 (16.8)
TT	Tc	16.6 (9.2)	23.5 (14.4)**	17.3 (10.3)
	Max F	5.04 (6.3)	6.9 (5.3)	4.7 (4.7)*
	Max P	16.3 (8.9)	31.5 (22.5)**	22.6 (19.9)*
TS	Tc	25.1 (12.6)	29.1 (11.4)	19.4 (10.9)
	Max F	5.7 (3.6)	6.8 (3.2)	4.1 (2.3)
	Max P	37.13 (20)	50.8 (25)	33.3 (10.3)
TF	Tc	37.2 (10.9)	41.9 (11.1)	23.2 (10.9)*,**
	Max F	16.5 (8.3)	10.7 (3.5)**	6.5 (2.6)*,**
	Max P	83.3 (28.1)	53.8 (16.1)**	46.8 (24.1)**

Tc: Total contact duration (St %), Max F: maximum vertical force (%BW), Max P: maximum peak pressure (kPa).
* Represents ($P < 0.05$) for preoperative vs postoperative comparison.
** Represents ($P < 0.05$) compared to control.

for the outcome assessment of HV surgeries. The strength of the study is the prospective design which helped to extract useful information that has strong implications in terms of functional recovery. Comprehensive assessment utilized in the study included the subjective questionnaires, the radiographic outcome and a complete gait assessment, hence providing detailed information of patient status.

Clinical implications of the study is that for the foreseeable modified Lapidus procedure to correct moderate to severe HV, the preoperative patient's information could help predict the possible level of outcome. Further, the optimization of postoperative rehabilitation could be achieved with early gait assessment. Importantly, clinical applicability of the nine defined gait characterizing parameters in HV deformity was confirmed for accurate assessment of the surgical outcome.

Table 3
Clinical assessment preoperatively and 6 months postoperatively; mean (SD).

Clinical assessment	HV (pre-operative)	Post Lapidus (post-operative)
FAAM-ADL	80 (17.05)	85.9 (14.3)
AOFAS – total (100)	46.4 (11.4)	85.2 (9.6)*
AOFAS – pain	17.5 (7.1)	31.25 (6.4)*
AOFAS – function	28.8 (8.9)	39 (4.2)*
M1/M2 (°)	15.6 (1.9)	5.5 (2.5)*
HVA (°)	32.7 (5.7)	10.7 (6.9)*
DMAA (°)	11.1 (4.9)	8.3 (4.7)

M1/M2: intermetatarsal angle, (M1/P1): hallux valgus angle, DMAA: distal metatarsal articular angle.
* Represents ($P < 0.05$).

5. Conclusion

In conclusion, the study strongly suggests the inclusion of gait assessment during early postoperative period following HV surgery with the potential clinical application that an individual's rehabilitation programs could be devised using the most accurate data for the best possible outcome. Furthermore, the robustness of the nine gait characterizing parameters in HV allows for accurate assessment in clinical practice. Additionally, for clinical foot and ankle research, these nine parameters could promote reliable comparison and promote consistency between the studies when determining future outcome.

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Outcome of Unilateral Ankle Arthrodesis and Total Ankle Replacement in Terms of Bilateral Gait Mechanics

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ABSTRACT: Previous studies assessed the outcome of ankle arthrodesis (AA) and total ankle replacement (TAR) surgeries; however, the extent of postoperative recovery towards bilateral gait mechanics (BGM) is unknown. We evaluated the outcome of the two surgeries at least 2 years post rehabilitation, focusing on BGM. 36 participants, including 12 AA patients, 12 TAR patients, and 12 controls were included. Gait assessment over 50 m distance was performed utilizing pressure insoles and 3D inertial sensors, following which an intraindividual comparison was performed. Most spatiotemporal and kinematic parameters in the TAR group were indicative of good gait symmetry, while the AA group presented significant differences. Plantar pressure symmetry among the AA group was also significantly distorted. Abnormality in biomechanical behavior of the AA unoperated, contralateral foot was observed. In summary, our results indicate an altered BGM in AA patients, whereas a relatively fully recovered BGM is observed in TAR patients, despite the quantitative differences in several parameters when compared to a healthy population. Our study supports a biomechanical assessment and rehabilitation of both operated and unoperated sides after major surgeries for ankle osteoarthrosis. © 2013 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res

Keywords: ankle arthrodesis; total ankle replacement; inertial sensors; plantar pressure parameters; bilateral gait

Osteoarthrosis (OA) of the ankle joint leads to both anatomical and biomechanical deterioration.[1–4] During the end stage of the disease, a compensatory gait pattern is often observed,[5] where a patient's asymptomatic contralateral foot bears an excessive and disproportionate load during dynamic activities. The result is the natural development of an asymmetrical gait pattern.[1]

Ankle arthrodesis (AA) and total ankle replacement (TAR) are frequently used surgical options to treat end-stage ankle OA. Ideally, the gait pattern improves 12 months postoperatively,[4,6] following completion of a physical rehabilitation program. To evaluate their outcomes in terms of pain and function, most studies utilize clinical questionnaires. Several of them reported no difference between treatments at mid-term follow-up.[7–9] However, more objective studies, utilizing gait analysis methods, reported a better outcome with TAR in terms of mobility.[3,6,10] Notably, these studies compared the operated foot with a control population and preoperative versus postoperative functional capabilities. No comprehensive information is available regarding the advantages of AA or TAR in terms of restoring bilateral gait mechanics (BGM).

Studies of the outcomes of other joint replacement surgeries, such as hip and knee, reported altered BGM after unilateral total joint arthoplasty.[11–13] These studies showed asymmetry in joint kinematics, moments, and loading due to increased load on the unoperated contralateral joint from a persistence of preoperative gait abnormalities. We aimed to investigate the outcome of AA and TAR looking at BGM. We hypothesized that, in light of promising clinical[7–9] or biomechanical[3,4,6,10] results from these procedures, a patient's BGM would be compromised after either surgery and that the effects are more likely observed in AA compared to TAR. We sought to qualify and quantify this gait asymmetry in terms of kinematics, kinetics and spatiotemporal parameters.

MATERIALS AND METHODS

Participants

36 participants were divided into three groups: 12 AA patients, 12 TAR patients, and 12 healthy controls. Consecutive patients with isolated post-traumatic end stage OA, who had undergone isolated AA or TAR, between 2003 and 2011, were evaluated. All surgeries had been performed by the senior author (XC) at the Orthopaedic Department of the University Hospital of Lausanne. The mean follow-up period postoperatively was 4.7 years (±2.7 years). Patients were excluded if they were affected by other pathologies of the spine and lower extremities.

To avoid bias towards patients with an inhomogeneous clinical outcome, the AOFAS ankle hind foot scale[14] was administered to determine if patients could participate. Patients with AOFAS score <70 for TAR and <60 for AA were excluded; these values were chosen according to the range reported in previous studies of TAR, using the same implants (Salto®, Tornier SA, Saint Ismier, France),[15] and of functional results following AA.[16] The lower score was considered for AA to compensate for bias due to the mobility subscale. The control population was volunteers with no prior history of lower limb pathology. All participants gave informed consent. Approval of the ethics commission of the University of Lausanne was obtained.

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Measurement System

Gait assessment was performed using an ambulatory pressure insole (Pedar-X, Novel, Germany) and five inertial sensors consisting of 3D accelerometers and 3D gyroscopes. The sensors were attached to the medial aspect of both tibias, and on the tested foot, to the posterior aspect of the great tuberosity of the calcaneus between the base of the first and second metatarsals, and on the dorsal aspect of the proximal phalanx of the first toe. Sensors were connected to two portable data-loggers (Physilog, BioAGM, CH). Each foot was measured separately. Insoles, with custom made sandals, were available in four sizes and were used according to the participants' shoe sizes. The setup, reliability, and accuracy of the applied gait assessment technology was previously validated.[2,17]

Measurement Protocol

To obtain repeatable joint angles consistently among subjects, the sensor signals and subsequent 3D joint angles were expressed relative to the foot and shank's anatomical frames, instead of the inertial sensors' technical frames.[17] To achieve this, a functional calibration based on passive knee movements was conducted.[18] After calibration, participants performed two walking trials at their natural pace in a straight line along a 50 m hospital corridor. The same procedure was repeated for the contralateral foot.

Spatiotemporal parameters, kinematics (joint angles) and plantar pressure were assessed for all gait cycles of each trial using previously validated algorithms.[2,19,20] The first and last three cycles of each trial were discarded to negate wayward effects during initiation and termination of walking. The average of all remaining gait cycles was then taken for each trial.

The spatiotemporal parameters included stance and swing phase gait cycle time (GCT), inner-stance events (loading, foot-flat, and push-off phases (stance phase %)), and heel strike pitch (HSP) and toe off pitch (TOP) angles. The HSP and TOP were included because they are associated with the chronology of the stance phase when the foot is loaded.

3D joint angles, during ambulation, were assessed in the sagittal (dorsiflexion/plantarflexion), coronal (inversion/eversion), and transverse (abduction/adduction) planes, for the following segments: forefoot-toes (FF-TO); hindfoot-forefoot (HF-FF); shank-hindfoot (SH-HF); and overall foot, shank-toes, (SH-TO).[21]

Plantar pressure parameters were assessed at 10 anatomical sub-regions: hindfoot (lateral and medial (HL, HM)); midfoot (lateral and medial (ML, MM)); forefoot (lateral, central and medial (FL, FC, FM)); and toes (divided into third to fifth toe (TT), second toe (TS) and first toe (TF)), based on a previously validated protocol.[17] The parameters assessed total contact duration (% stance time), maximum pressure (Max P) (kPa), and maximum vertical force (Max F) (% body weight). The gait data were analyzed using MATLAB version 2011a (The MathWorks, Inc.).

Outcomes were assessed for the operated (Op) ipsi-lateral and unoperated (Unop) contralateral foot and subsequently compared (AA Op vs. AA Unop and TAR Op vs. TAR Unop). Similarly, both sides of the control group were compared for each individual and, to avoid bias towards the dominant side, a further global comparison, randomizing sides of individuals, was conducted. Finally, both sides of each surgical option were compared to the controls.

Statistical Analysis

The average of each gait parameter over all gait cycles for each individual was compared between the operated (Op), unoperated (Unop) sides and between controls, using non-parametric statistical analyses. A Wilcoxon signed-rank test was performed to compare the intraindividual symmetry between the Op and Unop sides and a Wilcoxon rank-sum test for interindividual comparison between the Op groups and controls. The level of significance was alpha <0.05. The analyses were performed using Stata/IC12.0 (StataCorp). Median and inter-quartile range (IQR) of each parameter was calculated over all individuals in each population.

RESULTS

Demographics

No difference was seen between the two Op groups in age, weight, and BMI; however, the control group was significantly younger and healthier than the Op groups (Table 1). A significant difference occurred in the AOFAS hind foot scores between the two patient groups, ($p = 0.005$); this difference was in the function subscale ($p = 0.0004$), which is heavily weighted by the two mobility questions. Hence, pain and alignment subscales showed no difference between the two groups, representing fair homogeneous clinical results of the two surgeries.

Spatiotemporal Parameters of Gait

In the AA group, five of eight spatiotemporal parameters showed a significant difference ($p < 0.05$) between the Op and Unop sides, while the TAR group showed a significant difference in TOP only (Table 2). Significant differences were found against controls: the Op AA group (swing time, foot-flat, push-off, HSP, TOP); Unop AA (stance time, foot-flat, push-off, TOP); Op TAR (stance time, foot-flat, push-off, and TOP); and Unop TAR (stance time, swing time, foot-flat, push-off,

Table 1. The Demographic Parameters of Patients and the Participants in the Control Group

Physical Characteristics	TAR	AA	Control
Age (years)	63.6 (9.6)†	65.6 (8.3)†	45.6 (10.3)
Height (cm)	170.6 (7.5)†	164.1 (8.9)	165.3 (8.7)
Weight (Kg)	81.1 (15.2)†	74.5 (16.2)†	61.9 (12.5)
BMI (Kg/m^2)	27.74 (4.08)†	27.62 (5.4)†	22.5 (3.7)
Sex	8M, 4F	5M, 7F	3M, 9F
AOFAS hindfoot score	88 (11)†,*	66 (7)†,*	100 (0)

Values presented in median (IQR). †Represents significant difference ($p < 0.05$) compared to control, *represents significant difference ($p < 0.05$) between TAR and AA.

Table 2. Median (IQR) of Spatiotemporal Parameters of Operated/Un-operated Sides of Patients and Controls

Temporal Parameters	TAR Unop	TAR Op	AA Unop	AA Op	Control A	Control B
Stance (GCT)	60.3 (2.9)†	59.9 (3.8)†	63.4 (5.5)*,†	60.9 (5.5)*	57.65 (2.4)	58.87 (1.9)
Swing (GCT)	39.7 (2.9)†	40.5 (4.8)	41.3 (4.0)*	44.3 (3.1)*,†	42.4 (2.42)	41.1 (1.9)
Loading (St.%)	10.6 (1.9)	11.1 (3.6)	10.9 (5.1)*	15.5 (6.5)*	11.5 (3.2)	10.3 (2.3)
Foot-flat (St.%)	57.8 (2.7)†	56.8 (7.7)†	65.0 (10.7)†	65.01 (8.3)†	54.0 (9.1)	53.5 (5.4)
Push-off (St.%)	31.0 (2.7)†	32.8 (6.2)†	31.1 (5.3)†	29.9 (9.4)†	34.7 (8.2)	37.3 (5.2)
HSP (°)	20.1 (8.0)	21.8 (4.0)	20.6 (1.1) 1*	21.6 (7.2)*,†	21.3 (7.1)	19.0 (4.7)
TOP (°)	−71.5 (6.9)*,†	−64.9 (4.7)*,†	−51.0 (25.8)*,†	−30.3 (36.1)*,†	−78.8 (6.8)	−80.5 (2.8)

GCT, gait cycle time; St%, % of stance phase; HSP, heel strike pitch angle (the angle formed by the walking surface and the most posterior point on the heel at heel strike); TOP, toe off pitch angle (the angle formed by the walking surface and the toes at toe-off). *Indicates significant difference ($p < 0.05$) of Op-Unop comparison. †Represents significant difference ($p < 0.05$) compared to control average.

and TOP). Stance and TOP angle comparison is shown in Figure 1a–c.

Kinematics

The ROM between the Op and Unop sides of the AA group showed significant differences in: sagittal and coronal plane movements of FF-TO; sagittal and transverse plane movements of HF-FF; and movement in all three planes of SH-HF and SH-FF (Table 3). In contrast, a symmetrical joint movement was observed in the TAR group between the Op and Unop side except for a significant difference in sagittal and coronal plane movements of FF-TO and SH-HF, respectively. Comparing with the controls, significant differences were found in: Op AA group (all joint angles); Unop AA (sagittal plane movement of FF-TO); Op TAR (sagittal plane movement of FF-TO, HF-FF, SH-FF and coronal plane movement of SH-HF); and Unop TAR (transverse plane movements of HF-FF).

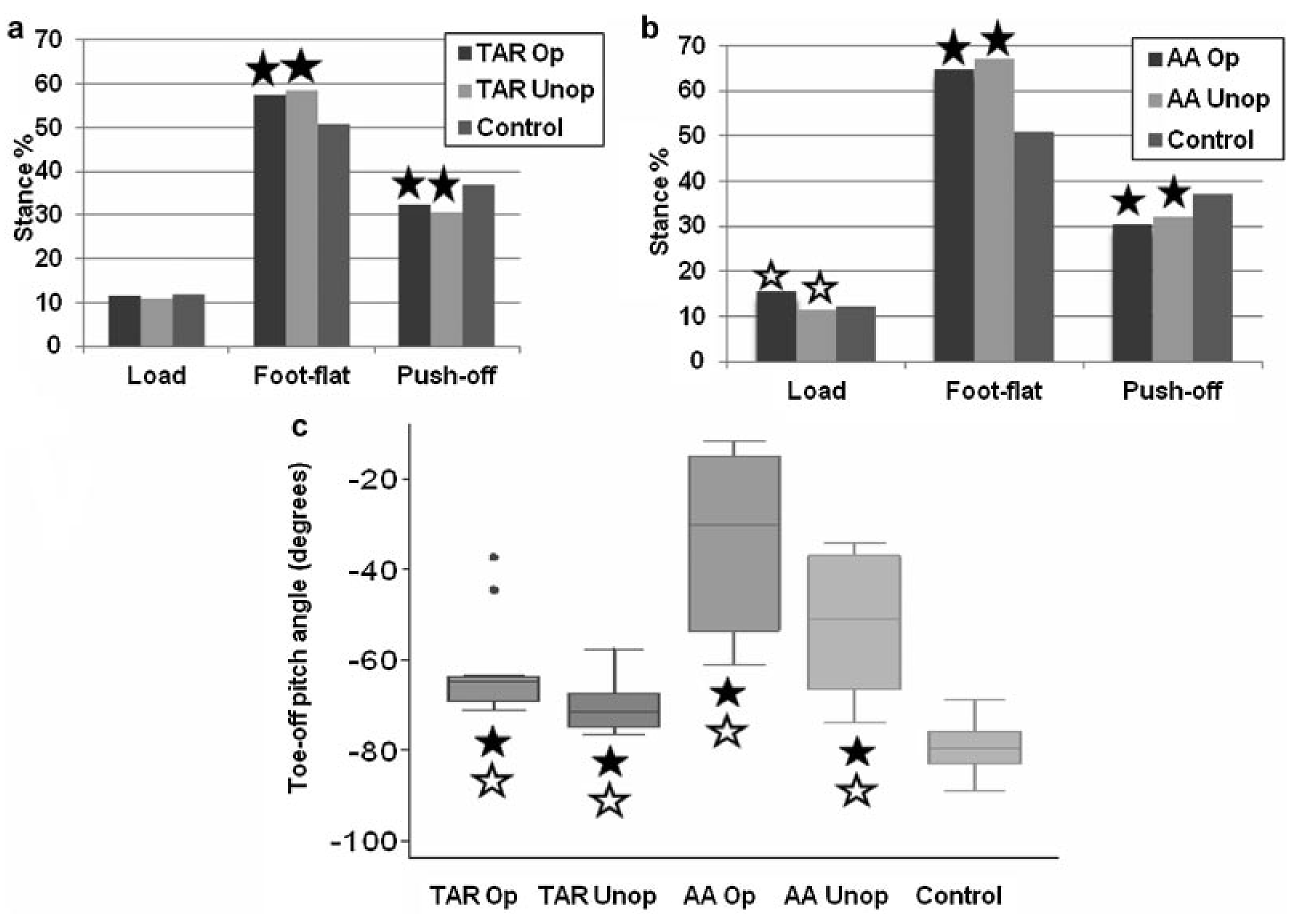

Figure 1. (a, b) Inter and intra-individual comparison of stance phase between the operated groups and controls, c. Inter and intra-individual comparison of TOP. ★ represents significant difference ($p < 0.05$) compared to controls. ☆ indicates significant difference ($p < 0.05$) of Op-Unop comparison.

Table 3. Median (IQR) of Joint Angles of Operated/Un-Operated Sides of Patients and Controls

Joints	Joint Movements	TAR Unop	TAR Op	AA Unop	AA Op	Control A	Control B
FF-TO	Dorsi-plantarflexion	38.4 (6.2)*	33.2 (13.9)*,†	35.1 (8.9)*,†	20.1 (10.9)*,†	42.6 (9.4)	41.7 (4.1)
	Inv-eversion	11.7 (2.7)	10.3 (2.3)	10.6 (4.8)*	7.3 (4.2)*,†	12.1 (5.2)	11.3 (5.6)
	Abd-adduction	9.4 (1.7)	8.5 (3.3)	9.8 (2.9)	10.2 (3.1)†	8.5 (4.4)	6.8 (4.5)
HF-FF	Dorsi-plantarflexion	23.9 (4.5)	18.9 (8.7)†	22.1 (4.5)*	10.4 (4.9)*,†	23.6 (5.6)	26.9 (4.2)
	Inv-eversion	7.9 (2.9)	6.8 (3.1)	6.3 (3.4)	5.1 (1.9)†	6.96 (3)	7.6 (2.2)
	Abd-adduction	4.2 (1.4)†	5.8 (5.9)	7.3 (2.4)*	3.5 (2.6)*,†	6.2 (1.96)	6.2 (1.98)
SH-HF	Dorsi-plantarflexion	13.9 (7.3)	9.6 (5.4)†	12.8 (4.9)*	10.3 (4)*,†	13.4 (2.5)	12.1 (1.7)
	Inv-eversion	12.7 (3.7)*	6.7 (2.4)*,†	11 (3.0)*	7 (2.4)*,†	12.3 (6.2)	10.2 (3.1)
	Abd-adduction	8.7 (5.6)	7.81 (2.2)	9.7 (3.9)*	5.8 (2.1)*,†	8.5 (3.7)	9.7 (5.7)
SH-FF	Dorsi-plantarflexion	26.8 (4.3)	30 (6.8)	27.2 (4.6)*	15.5 (4.3)*,†	32.1 (5.6)	31.5 (4.96)
	Inv-eversion	18.8 (5.5)	14.6 (4.4)	14 (2.9)*	7.1 (2.1)*,†	17.5 (7.8)	13.1 (4.0)
	Abd-adduction	9.3 (4.7)	10.8 (5.7)	10 (2.8)*	6.5 (3.7)*,†	10.1 (4.4)	14.6 (4.6)

TO, toes; FF, forefoot; HF, hindfoot; SH, shank. *Indicates significant difference ($p < 0.05$) of Op-Unop comparison. †Represents significant difference ($p < 0.05$) compared to control average.

Plantar Pressure Parameters

In 8 of 10 sub-regions (HL, HM, ML, MM, FL, FC, FM, TF), Tc results showed significant differences between the two sides of the AA group (Table 4). Max P and Max F were significantly different in 6 of 10 (HM, MM, FC, FM, TT, TS) and 3 of 10 (FC, FM, FT) sub-regions, respectively. All together, 17 of 30 plantar pressure results were significantly different,

Table 4. Median (IQR) of Plantar Pressure Parameters of Operated/Un-operated Sides of Patients and Controls

Foot Region	Plantar Pressure	TAR Unop	TAR Op	AA Unop	AA Op	Control A	Control B
Hindfoot lateral	Tc (St.%)	55.10 (15.1)	51.8 (14.5)†	87.1 (20.4)*,†	55.4 (18.1)*,†	45.4 (5.2)	49.9 (5.7)
	Max P (kPa)	96.11 (37.2)*	77.7 (20.4)*	113.9 (52.4)	121.9 (67.1)	97.3 (49.2)	109 (43.6)
	Max F (BW%)	23.2 (10.5)*,†	17.97 (8.5)*	26.2 (12.5)	27.5 (15.2)	34.6 (15.1)	29.4 (15.2)
Hindfoot medial	Tc (St.%)	55.80 (16)†	54.54 (11.4)	89.8 (26.4)*,†	53.1 (18.3)*,†	50.4 (5.3)	53.6 (6.5)
	Max P (kPa)	120.2 (57.5)	109.7 (53.5)	130.8 (91.9)*	86.2 (62)*,†	108.6 (49.9)	141.0 (34.2)
	Max F (BW%)	32.9 (16.7)	29.2 (13.9)†	40.9 (28)	26.0 (21.2)	36 (9.0)	40.2 (11.9)
Midfoot lateral	Tc (St.%)	61.1 (15.6)†	59.2 (9.6)†	101.8 (37.7)*,†	61.2 (21.3)*,†	31.6 (34.8)	37.7 (12.6)
	Max P (kPa)	32.7 (28.2)†	41.7 (14.6)†	55.8 (19.3)†	59.1 (29.2)†	13.7 (13.1)	18.7 (8.8)
	Max F (BW%)	10.3 (13.5)†	15.2 (4.3)†	23.3 (9.5)†	16.2 (12.2)†	5.5 (4.1)*	8.2 (5.8)*
Midfoot medial	Tc (St.%)	31.54 (28.1)†	34.54 (13)†	65.1 (16.9)*,†	26.5 (27.1)*,†	23.6 (19.2)	21.9 (19.4)
	Max P (kPa)	9.9 (10.4)	14.5 (3.9)†	17.1 (9.5)*,†	10.8 (7.9)*	10.6 (7.3)	8.9 (4.2)
	Max F (BW%)	3.3 (4.4)	3.7 (2.3)	5.8 (3.5)†	5.5 (3.6)	2.5 (4.2)	1.2 (2.5)
Forefoot lateral	Tc (St.%)	84.7 (14.9)	83.8 (9.1)†	123.5 (22.4)*,†	76.8 (12.6)*	79.5 (16.5)	83.1 (5.1)
	Max P (kPa)	102.3 (56.7)	117.4 (43.1)	128.1 (67.4)	129.7 (48.4)†	111.6 (29.4)	114.6 (28.6)
	Max F (BW%)	28.5 (7.1)	25.1 (14.7)	36.1 (14.5)	32.4 (13.5)	30 (9.3)	30.4 (9.8)
Forefoot central	Tc (St.%)	77.5 (13.6)	70.6 (13.3)	117.04 (28.8)*,†	64.8 (17.7)*	70.4 (24.3)	73.5 (11.6)
	Max P (kPa)	151.7 (43.5)	125.9 (47.3)	177.6 (63.6)*,†	111.7 (40)*	123.6 (18.4)	141.2 (31.7)
	Max F (BW%)	27.5 (5.1)	21.8 (8.9)†	32.4 (12.3)*,†	24.5 (9.4)*,†	28.9 (3.4)	29.8 (4.9)
Forefoot medial	Tc (St.%)	72.9 (30.1)†	55 (16.1)	91.5 (25.1)*,†	40.8 (23.3)*	42.3 (28.9)	53.3 (16.1)
	MaxP (kPa)	86.3 (49.5)†	62.6 (27.3)	100.9 (53)*,†	43.7 (23.8)*	52.7 (33.4)	61.6 (18.5)
	Max F (BW%)	19.2 (8.7)	11.1 (8.4)	17.5 (14.7)*,†	8.7 (5)*,†	13 (9.5)	14.4 (4.5)
Third toe	Tc (St.%)	12.4 (10.6)	11.8 (13.8)	26.4 (9.1)†	23.5 (23.6)	15.3 (9)	11.6 (15.5)
	Max P (kPa)	12.0 (7.0)	9.2 (13.4)	25 (4.9)*,†	15.9 (12.4)*	13.9 (6.6)	14.2 (10)
	Max F (BW%)	2.1 (2.4)	0.9 (3.6)	3.8 (1.8)	3.0 (3.9)	3.5 (3.9)	2.8 (4.8)
Second toe	Tc (St.%)	29.5 (13.3)*	32.3 (9.5)*	31.3 (18.5)	16.9 (20.4)	29.6 (17.6)	29.5 (11.7)
	Max P (kPa)	35 (13.9)	41.1 (19.4)	56.6 (43.8)*	43.3 (25.6)*	32.8 (12.2)	40.7 (6.2)
	Max F (BW%)	4.9 (2.5)	5.6 (3.1)	5.1 (6.4)	4.4 (3.2)	5.8 (3.5)	7.3 (4.1)
First toe	Tc (St.%)	33.9 (15.1)	37.6 (8.7)	47.3 (23.5)*	20.5 (13.5)*,†	35.3 (17.3)	38.4 (15)
	Max P (kPa)	70.7 (39.2)	55.4 (42.3)	113.5 (65.6)	44.3 (23.2)†	91.5 (40.5)	81 (28)
	Max F (BW%)	9.4 (7)	9.5 (6.6)†	11.3 (8.4)*,†	5.7 (4.7)*,†	18.3 (10.6)	13.5 (11.8)

*Indicates significant difference ($p < 0.05$) of Op-Unop comparison. †Represents significant difference ($p < 0.05$) compared to control average.

indicating bilateral asymmetry in the AA group. Similar comparison in the TAR group showed significant difference in 3 of 30 plantar pressure results (HL (Max P and Max F) and TS (Tc)). Hence, the TAR group showed better BGM in plantar pressure compared with the AA group. Comparing with the controls, significant differences were seen in; AA Op (13 out of 30); AA Unop (18 out of 30); TAR Op (12 out of 30); and TAR Unop (8 out of 30). Comparison of the mean difference of maximum force among each group is shown in Figure 2.

DISCUSSION

Both AA and TAR surgeries are associated with residual ipsilateral biomechanical abnormalities.[22–24] Our results show that, at least two years after rehabilitation, TAR patients demonstrated BGM comparable to the controls. Conversely, AA patients showed persistent BGM alterations.

Spatiotemporal Parameters of Gait

In the stance phase of the AA and TAR groups, both Op and Unop sides showed significantly longer

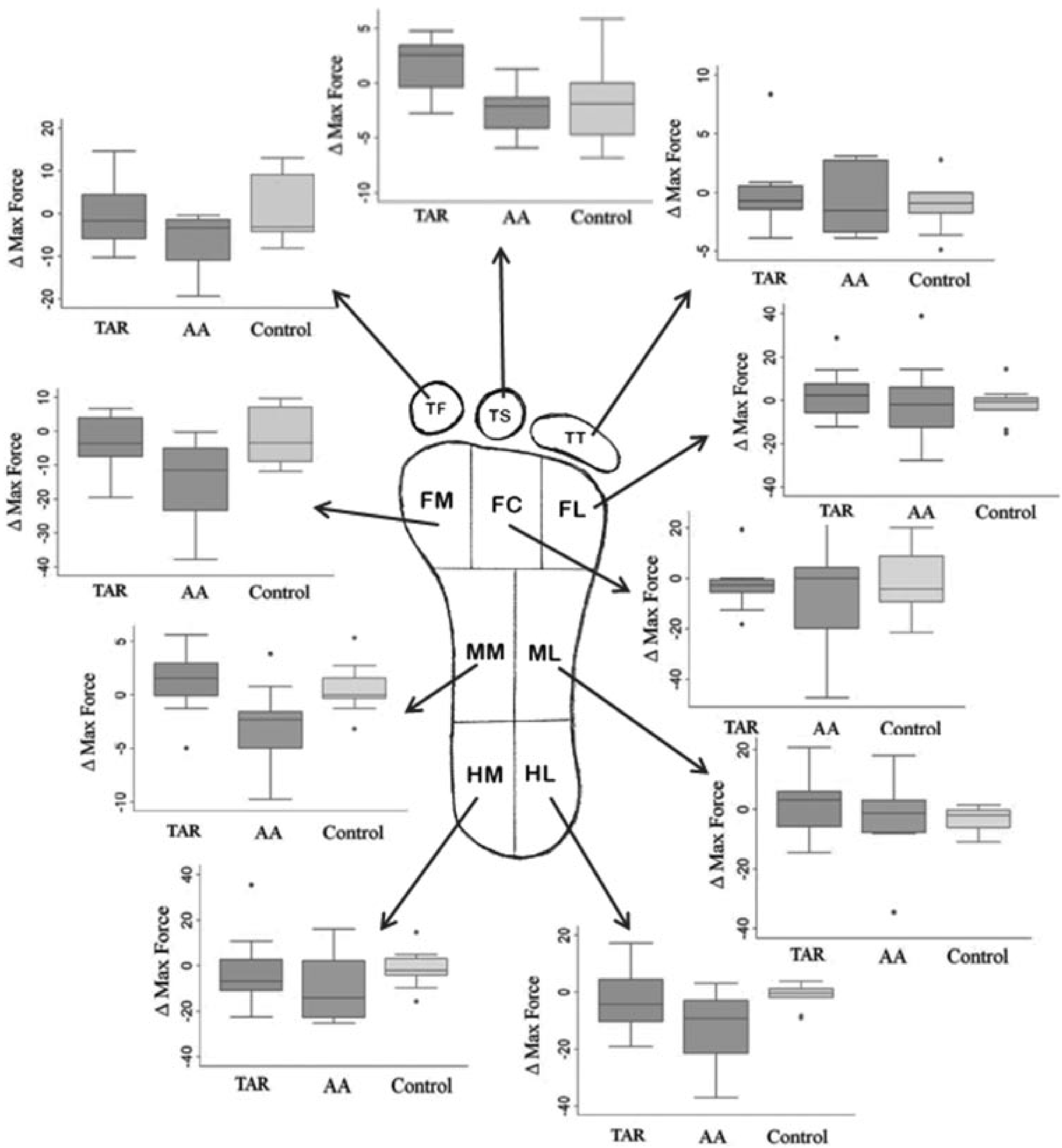

Figure 2. Box and whisker plots representing mean difference of maximum force (Δ Max Force) in 10 foot regions between operated and unoperated sides of AA, TAR and the two sides of controls. HL, hindfoot lateral; HM, hindfoot medial; ML, midfoot lateral; MM, midfoot medial; FL, forefoot lateral; FC, forefoot central; FM, forefoot medial; TT, third to fifth toes; TS, second toe; TF, first toe. Force normalized to body weight %.

foot-flat and shorter push-off durations compared to controls (Fig. 1a,b), corresponding to a previous study by Mariani et al.[19] Notably, the durations on the Unop sides of both groups adapted according to their Op sides. Comparatively longer foot-flat duration in both sides of the AA group represent a slower walking pace. Also, the smaller TOP observed in both AA and TAR group compared with controls could be due to the weaker push-off. However, this difference with the controls was smaller in the TAR group (Fig. 1c). Spatiotemporal results show that AA, unlike TAR, patients show deterioration in their gait symmetry, representing an altered BGM.

Kinematics

The kinematic outcome of all three groups were consistent with previous studies,[3,17,25] though a higher ROM in sagittal plane midfoot movements was observed, consistent with Scott and Winter,[26] who reported transverse tarsal movements between 10° and 20°. No explanation for this increase in amplitude exists; however, it is likely due to differing preferred walking speeds amongst participants; our participants, walking at a comparatively slow pace, bore longer plantar flexion during the last 5–10% of stance in the mid foot region.

Comparing the AA group with controls, a reduced ROM was observed throughout; all joint angles for Op side, 10 of 12 for Unop side. Previous studies focused on hindfoot and midfoot mobility whereas our results detail a significant reduction in first toe mobility in the sagittal and coronal planes after AA and TAR surgeries. As before, the overall joint ROM results prove better in TAR patients compared to AA.

Plantar Pressure Parameters

We report that the Tc of the Op AA side is significantly smaller compared with Unop side in most sub-regions, differing from Schuh et al.,[27] who reported a decrease in Tc only in the forefoot and toe regions. Our results also show a significant increase in the Tc of AA patient's Unop side in all regions compared to the controls. A compensatory gait pattern in AA patients is due to these issues present in the Op foot. TAR patient results show good symmetry in Tc, comparable to the controls.

Specific regions in the foot take Max P during ambulation.[28] Studies comparing the normal regional peak pressure distribution showed notable continuity among healthy individuals.[29,30] The regional Max P typically follows a triangular pattern: medially at hindfoot to laterally at the midfoot to centrally in forefoot and finally to the first toe region. Our results show similar peak pressure regions bilaterally in the control and TAR groups; however, AA patients bore a lateral displacement of pressure on their Op foot. Similar results were reported by Rouhani et al.[2] For AA patients, abnormal reduction in Max P was seen on the medial sub-regions of the hindfoot, midfoot, and forefoot regions compared to the Unop side. Interestingly, the Max P on the lateral subregions of the Op side was not different to the Unop side, representing a relative lateral shift of Max P on the Op AA foot. Tthe Unop AA foot also showed an increase in Max P at all regions compared to controls, showing a clear pressure imbalance for AA patients. Previous studies comparing Op AA foot with the contralateral Unop foot (Schuh et al. and Fuentes-Sanz et al.) failed to demonstrate this pressure imbalance as they did not separate all foot regions into lateral and medial sub-regions.[25,31]

In box plots (Fig. 2), the medians of control and TAR groups were closer to zero in most regions, representing symmetrical loading, but in the AA group the median was far below zero in the medial sub-regions of hindfoot, midfoot, and forefoot representing asymmetrical loading between sides. A similar comparison by Schuh et al. for AA patients only reported differences in the lateral, midfoot region. Fuentes-Sanz et al.[31] reported no difference in the maximum force between Op and Unop sides of AA patients.

Schuh et al. compared the Op side with the asymptomatic contralateral side and reported no difference in Max F, Max P of hindfoot, medial midfoot and forefoot regions of either foot, or Max P in the lateral midfoot region of the Op foot. Fuentes-Sanz et al. showed no difference in gait, spatiotemporal, or kinematic and kinetic parameters between the Op and Unop feet of AA patients. These different results compared to our findings are due to aspects of their assessment procedures including: (a) value of Max F was not normalized to body weight and, hence, not a reliable interpreter; (b) foot models were divided into only five and six sub-regions, respectively; (c) pressure data were collected using fixed location pressure platforms. The use of a pressure platform, which makes patient's apprehensive during this section of each walking trial, leads to an adverse effect on their walking pace/mechanics; mobile pressure insoles mitigate this issue and provide data throughout the walking trial.

Our findings draw attention to the negative impact of ipsilateral AA on the contralateral foot, leading to altered BGM. For several gait parameters, especially plantar pressure parameters, the difference of the non operated foot to the controls was even more than that of the operated foot to the controls. This could support extended indications for TAR. However, the decision to perform TAR or AA depends on other criteria beyond our biomechanical findings. Promoting an intense rehabilitation program for either surgery and for both feet could be beneficial. Patient education regarding gait mechanics and breaking the adapted abnormal BGM post surgery would also help. Gait assessment 6 months postoperatively is recommended as a prognosis measure. Any significant alteration during the early rehabilitation stages could be corrected with the help of orthosis/insoles or a change of rehabilitation protocol based on the patient's requirements and could lead to an overall improvement in BGM after either surgery.

The strength of our study is its design and gait analysis technology. Both Op and Unop sides were compared to assess BGM and subsequently compared with the controls to determine the deviation from the ideal. Also, we provide the first comprehensive biomechanical profile of the asymptomatic Unop foot after AA and TAR, which was disregarded in previous studies. Finally, the gait analysis system allowed comparison of data recorded over a long walking distance, reflecting a more natural gait pattern compared to recordings of only a few steps.

Our study has limitations. The small population questions the validity of the results; however, differences in parameters reached and exceeded reputable levels of significance. Several previous gait studies of AA and TAR involved a similar number of patients per group.[3,10,25] Valderrabano et al. justified the use of smaller population by calculating power based on a pilot study. The presence of pre-operative data would have provided information with regards to altered BGM in case of end stage ankle OA and to what extent this alteration was reduced after successful TAR or AA; however, from the *posteriori* knowledge, the distorted gait parameters in end stage OA is known.[1,4] The non randomization of the allotted treatment is another limitation; however, randomization is ethically unacceptable in patients with post traumatic end stage OA because the decision to perform either AA or TAR depends on various factors. The absence of randomization could bias the results in comparing the two groups. But we did not aim to compare the superiority of one surgery over the other; rather, the major implication was to understand BGM after either. Measurements were performed on one foot at a time; however, this method should not affect the results due to high test-retest repeatability.[2,3] The significantly different demographics of the controls compared with the cohorts could be a limitation; however, our aim was to compare intraindividual results and not patients vs. controls. The control group was added to assess the level of gait deviation. Finally, spanning eight years (2003–2011) for recruitment may appear large; however, the minimum follow up was 2.7 years and, in our experience, the clinical situation is stabilized 2 years postoperatively.

In conclusion, we found significantly altered gait mechanics in the unoperated side of AA patients. In clinical terms, our findings demonstrate that patients who received TAR had a good ROM, less limp, and a well balanced gait. AA patients, however, exhibited restriction in their operated side and were consistently more dependent on their unoperated side for support. These findings suggest that rehabilitation should also consider the unoperated side after major surgeries for ankle OA. Furthermore, our study supports the need for assessment of both operated and unoperated sides when determining the outcome of TAR and AA and that this principle should be applied when evaluating all foot and ankle pathologies and their respective treatments.

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Biomechanical Outcome of Tibiotalocalcaneal Arthrodesis and Ankle Arthrodesis

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ABSTRACT

Background: Gait alterations including gait asymmetry have been reported to follow ankle arthrodesis, however, not much information is available regarding tibiotalocalaneal arthrodesis. The study aimed to functionally assess and compare the gait mechanics following both the surgeries.

Methods: 36 participants, including 12 patients from each of the two surgical groups and 12 healthy age matched controls, were assessed using clinical scores and ambulatory gait analysis, utilizing pressure insoles and 3D inertial sensors. Both operated and unoperated sides of patients were tested and compared based on 47 measured gait parameters.

Findings: Both case groups reported reduced hindfoot and forefoot motion, decreased cadence, speed, and stride length, increased foot flat phase, and increased loading duration of the hindfoot and the lateral midfoot. Ankle arthrodesis patients also reported overloading of the unoperated hindfoot, midfoot and forefoot, representing extensive bilateral asymmetry.

Interpretation: Our findings reject the hypothesis that tibiotalocalcaneal arthrodesis, with greater articular restriction, is more detrimental for gait mechanics than ankle arthrodesis. Specifically, considering plantar pressure parameters, tibiotalocalcaneal arthrodesis reported better outcome in terms of bilateral gait mechanics. Future research should aim to determine which pathologic gait parameters are predictive for long term outcome.

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INTRODUCTION

Tibiotalocalcaneal arthrodesis (TTCA) involves fusion of both tibiotalar and subtalar joints. It is an established surgical procedure for combined end stage diseases of the ankle and subtalar joints. It is also used as a salvage procedure for failed ankle and hindfoot surgery [2, 7]. Several fixation methods are available for TTCA [2, 4, 7], out of which retrograde intramedullary nailing has been reported to be associated with good initial stability and positive outcome [2, 4, 13]. Few studies have assessed the outcome of TTCA in comparison to other ankle surgeries, most of which utilize radiographic assessment and clinical scores [2, 4, 7]. Furthermore, biomechanical studies of TTCA are mostly in-vitro cadaveric studies which are not representative for functional biomechanics [3, 17]. Limited data is available regarding gait alterations following TTCA [24].

On the other hand, Ankle arthrodesis (AA) involves fusion of only tibiotalar joint and is a well documented and widely used procedure to address end stage diseases of the ankle joint [25]. Several studies have assessed the outcome of AA, giving mixed outcome based on the assessment method used. Studies assessing AA based on the clinical scores and pain assessment has continued to report good to excellent outcomes [4, 10, 25], however, studies assessing the biomechanical outcome following AA reported significant alterations in gait mechanics. Peak pressures during walking at hindfoot and forefoot [23] has been found to be shifted laterally [6, 20]. Such an alteration, result in the adaptation to a compensatory gait mechanics in adjacent joints, both ipsilaterally, as well as at the contralateral side to achieve the most economical gait pattern [6, 20, 25] . Furthermore, studies assessing the long term outcome of AA, based on radiographic results, reported arthritic changes in neighboring joints [8, 11].

With the current state of knowledge regarding AA, as well as limited gait mechanics information following TTCA, one may assume that gait alteration would be higher in TTCA patients because of the fusion of both tibiotalar and subtalar joints. The goal of the present study is to provide a comprehensive bilateral gait assessment following TTCA and AA to compare the outcomes. The working hypothesis is that, due to further articular restriction, the gait alteration and inherent asymmetry following surgical correction would be greater in TTCA comparison to AA.

MATERIALS AND METHODS

Participants

This is a retrospective cohort study, reporting the evidence level of III. The study involved 36 participants, including 12 AA patients, 12 TTCA patients and 12 healthy controls. TTCA group consisted of patients, who had the surgery either as a salvage procedure for failed total ankle arthroplasty or as a primary procedure for simultaneous ankle and subtalar osteoarthrosis. The AA group consisted of patients with post-traumatic end stage ankle osteoarthrosis, who had undergone isolated AA, during the same period and were selected based on the same exclusion criteria as the TTCA group. The average follow-up period, was 4.5±2 years. All surgeries had been performed by the senior author. The control population consisted of volunteers who had no prior history of lower limb pathology or injury. Study population demographics are presented in Table 1. All participants gave their informed consent. Approval of the ethics commission of the University was obtained.

Table 1: Demographics and Clinical Scores

Demographics & Clinical Scores	TTCA	AA	Control
Age (years)	63.6 (9.6) †	65.6 (8.3) †	54.4 (5.9)
Height (cm)	174 (6.7) †	164.1 (8.9)	165.3 (8.7)
Weight (Kg)	86.7 (17) †	74.5 (16.2) †	61.9 (12.5)
BMI (Kg/m^2)	28.6 (5.8) †	26.5 (4.5) †	22.5 (3.7)
Sex	7M, 5F	5M, 7F	3M, 9F
AOFAS-hindfoot	66 (10.1)	65 (6.8)	-
FAAM-ADL	72 (16.4)	68.8 (17.6)	-
EQ5D	0.67 (0.2)	0.66 (0.16)	-

* Indicates significant difference ($p<0.01$) of Op-Unop comparison. †Represents significant difference ($p<0.01$) compared to control average. ¶ Represents significant difference ($p<0.01$) of TTCA Op and AA Op side comparison

Clinical Assessment

Clinical evaluation included the American Orthopedic Foot and Ankle Society (AOFAS) Hindfoot Score [14] and the Foot and Ankle Ability Measure Score (FAAM)- activity of daily living (ADL) section [5], in conjunction with the general health specific score EQ5D [12]. For FAAM, the sport section of the score was ignored by most patients in the two case groups and as such was not included.

Gait Assessment

Ambulatory gait assessment included the use of pressure insoles (Pedar-X®, Novel, Germany) and four inertial sensors each consisting of 3-D accelerometers and gyroscopes. The system had been previously validated and shown to have high test-retest reliability [20, 21]. Sensors were placed, on the medial border of the shank (both sides), posterior calcaneal tuberosity and between the bases of the first and second metatarsal, following a previously validated protocol [21]. Sensors were connected to two portable data acquisition systems (Physilog®, BioAGM, CH). Pressure insoles were available in four sizes, with custom made sandals.

Functional calibration was performed in accordance with the previously published study [9], following which participants performed two 50 m walking trials at their natural speed in a hospital corridor. In the case groups, both operated (Op) and unoperated (Unop) sides were tested for the evaluation of gait symmetry.

For gait data analysis, all gait cycles of the two trials, except the first and last three gait cycles of each trial, were included. This was done to negate unsteadiness during the initiation and termination of walking. While for plantar pressure parameter assessment the foot was divided into 10 different anatomical sub-regions for an elaborate understanding of plantar loading. The 10 foot subregions include: hindfoot (lateral and medial (HL, HM)), midfoot (lateral and medial (ML, MM)), forefoot (lateral, central and medial (FL, FC, FM)) and toes (divided into third to fifth toe (TT), second toe (TS) and first toe (TF)) [20]. And the parameters assessed included total contact duration (Tc) (% stance time), maximum pressure (Max P) (kPa), and maximum force (Max F) (% body weight). For kinematic assessment, a validated multisegment foot model was used [21]. Kinematics data were recorded in the sagittal, coronal and transverse planes over 100% of the stance phase. Based on the joint coordinate system the inter-segment joint range of motion (ROM) during ambulation was assessed for the following segment couples: forefoot-hindfoot, hindfoot-shank and forefoot-shank. Lastly, the spatiotemporal parameters of gait included: cadence, stance, stride, speed, peak angular velocity and inner-stance events (loading, foot-flat, and push-off phases expressed in % of stance phase) [15].

Statistical data analysis

The average of each gait parameter over all gait cycles was calculated separately for both sides of each individual. Shapiro-Wilk test of normality showed normal distribution in half of the parameters. Hence both non-parametric (Wilcoxon rank sum/ Wilcoxon signed-rank tests) and parametric (unpaired and paired student t test) tests were used to compare case groups with the controls and to compare Op and contralateral Unop sides of both case groups, respectively. The level of significance was set at $p < 0.01$ to prevent the likelihood of false positive results due to multiple parameters and multiple comparisons. Data were analyzed and compared using MATLAB version 2011a (The MathWorks Inc.)

RESULTS

Demographics and Clinical Scores

Demographic comparison showed no significant difference between the two case groups. However, compared to the controls, both case groups were, on average, older and heavier (Table 1). The outcome of all three clinical scores was similar in both case groups, suggesting comparable clinical status of the patients in the two groups.

Plantar Pressure Parameters

Plantar pressure parameters results in 10 sub regions of the foot are summarized in Table 2. Comparing the Op side of AA patients to the controls, the following significant differences were observed: (Tc) was longer in the HL, HM, ML and shorter in the TF; (Max P) was higher in the ML, FL and lower in the TF (Max F) was higher in the ML and lower in the TF. In comparing the Unop side with the controls, significant differences were found in 11 out of 30 parameters, including: longer (Tc) in the HL, HM, ML, MM, FC and FM; higher (Max P) in the ML, MM, and FM; higher (Max F) in the ML, and MM.

Table 2: Median (IQR) of plantar pressure parameters (PPP) of gait

Foot segments	PPP	TTCA Op	TTCA Unop	AA Op	AA Unop	Control
Hindfoot Lateral	Tc	65.7 (17) †¶	64.9 (23.5) †	52.6 (16.6) *†¶	87.7 (14.8) *†	46 (9)
	Max P	124.8 (57)	122.3 (68)	121.9(67.1)	121.6 (50.5)	106 (54.6)
	Max F	28.6 (15.9)	30.3 (17.9)	27.4 (15.5)	28.2 (17.5)	29.4 (16)
Hindfoot Medial	Tc	64.1 (12) †¶	74.7 (17.1) †	51.9 (17.8) *†	90.1 (15.6) *†	48.9 (9.7)
	Max P	143.1 (42.8) ¶	124.5 (63.6)	78.9 (42.9) *¶	129.2 (104.4)*	142.7 (40.2)
	Max F	40.3 (8.9)	35.7 (14.7)	24.9 (21.4)	38.6 (31.3)	39.1 (9.6)
Midfoot Lateral	Tc	56.8 (7.5) †	69.6 (18.7) †	59.1 (19.3) *†	106(12.2) *†	35.9 (5.7)
	Max P	54.5 (16.9) †	44.1 (27.6) †	59.1 (29.2) †	55.6 (29.2) †	17.4 (6.9)
	Max F	18.1 (6.4) †	18.5 (5.1) †	16.2 (8.3) †	23.3 (9.5) †	7.4 (3.7)
Midfoot Medial	Tc	43.2 (6.6)	54.5 (30.6)	23.7 (25.4) *	65.9(19.3) *†	37 (11.7)
	Max P	21.07 (5.4) ¶	21.5 (17.6)	9.7 (7.7) ¶	16.9 (9.1) †	10.6 (7.3)
	Max F	5.6 (2.2)	6.6 (6.7)	3.96 (3.7)	5.7 (3.6) †	2.5 (2)
Forefoot Lateral	Tc	81.5 (11.5)	85.1 (4.8)	78.1 (13) *	123.5 (22.4) *	77.8 (24.6)
	Max P	142.8 (21.7)	109.6 (22.98)	128 (19.4) †	140.9 (66.4)	114.6 (22.3)
	Max F	34.8 (6.9)	27.2 (12.9)	31.3 (9.3)	36.5 (13.4)	33.6 (9.8)
Forefoot Central	Tc	71.1 (12.6) *	81.4 (2) *	62.3 (20.9) *	118.7 (19.9) *†	70.4 (24.3)
	Max P	136.2 (24.4)	126.7 (51.9)	110.8 (35.1) *	173.1 (60.7) *	141.2 (35.5)
	Max F	27.9 (6.8)	24.3 (8.6)	22.7 (8.6)	31.7 (10.2)	28.9 (3.4)
Forefoot Medial	Tc	63.8 (11.2) †	66.6 (12) †	40.4 (25.3) *	91.9 (26.4) *†	40.3 (18)
	Max P	74.7 (18.1) ¶	67.9 (41.7)	39.9 (26.6) *¶	100.8 (66.7) *†	53.9 (18.5)
	Max F	16.3 (3.1) ¶	14.3 (6.6)	7.8 (4.9) *¶	17.1 (12.6) *	13 (3.8)
Third Toe	Tc	27.7 (11.9)	34.9 (16)	23.5 (23.6)	26.4 (9.1)	19.5 (11)
	Max P	15.8 (7.9)	18.3 (8)	15.9 (12.4)	25 (4.9)	13.9 (6.6)
	Max F	3.2 (1.9)	4.6 (1.7)	3.0 (3.9)	3.8 (1.8)	4.5 (3.4)
Second Toe	Tc	36.1 (5.7)	42.5 (13.7) †	16.9 (20.4)	31.3 (18.5)	25 (16)
	Max P	52.7 (12.5)	51.9 (15.2)	43.3 (25.6)	56.6 (42.6)	40.7 (6.2)
	Max F	5.2 (2.5)	6.8 (3.1)	4.4 (3.2)	5.1 (6.4)	5.2 (3.5)
First Toe	Tc	30.5 (7.4)	46.3 (26.3)	21 (15) *†	45 (19) *	35.3 (7.9)
	Max P	64.9 (18.1) †	70.98 (15.9)	52.2 (25) †	93.2 (76.1)	81 (26.4)
	Max F	8.6 (2.9)	12.4 (2.9)	5.7 (5.1) †	9.7 (5.4)	13.4 (10)

* Indicates significant difference ($p<0.01$) of Op-Unop comparison. † Represents significant difference ($p<0.01$) compared to control average. ¶ Represents significant difference ($p<0.01$) of TTCA Op and AA Op side comparison, Group p value represents normality

Comparing the TTCA group's Op side to the controls, the following significant differences were observed: (Tc) was longer in the HL, HM, ML and FM; (Max P) was higher in the ML and lower in the TF; (Max F) was higher in the ML. In comparing the Unop side with the controls, significant differences in 7 out of 30 parameters including: longer (Tc) in the HL, HM, ML, FM, and TS; higher (Max P) in the ML; higher (Max F) in the ML.

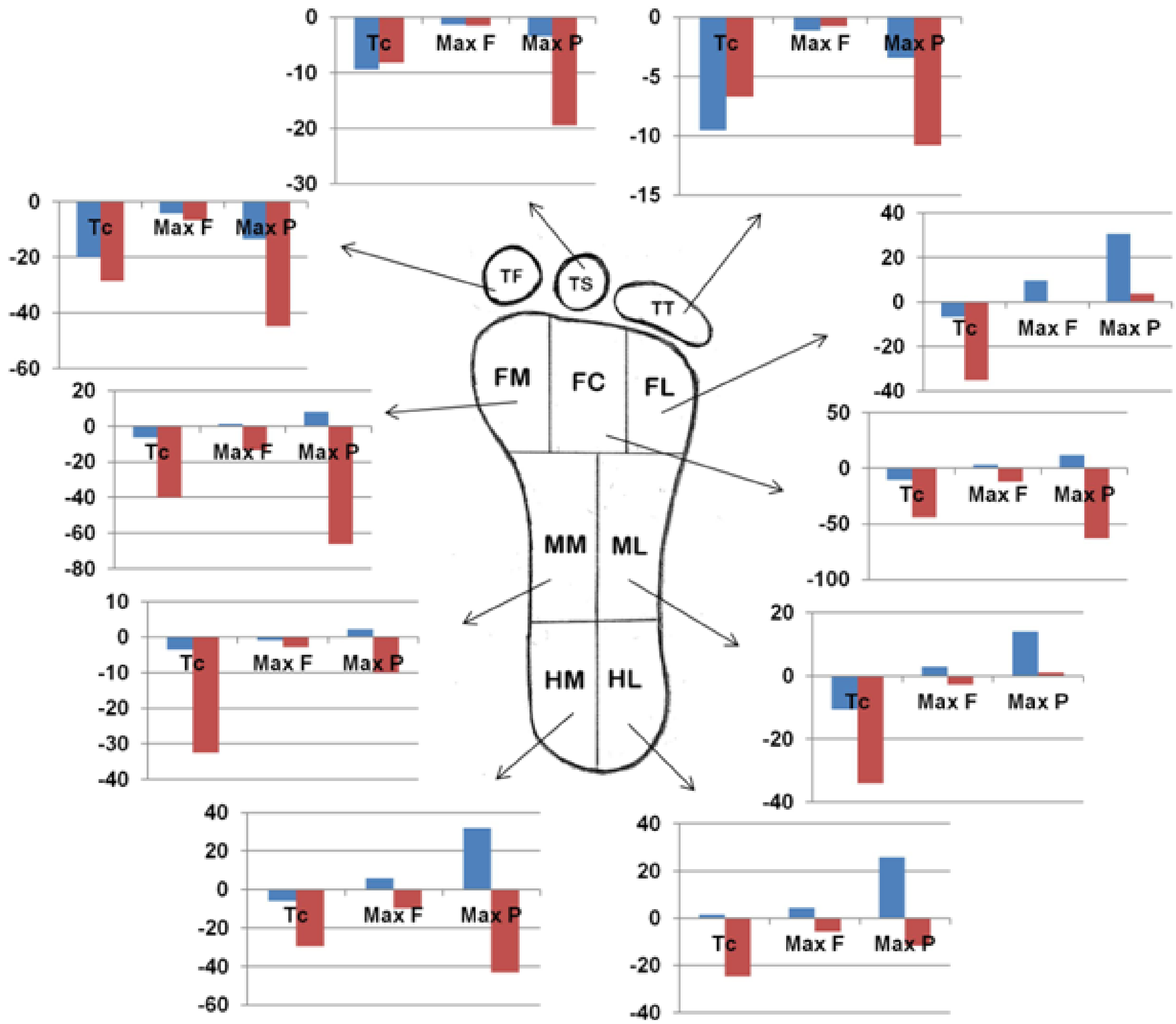

Figure 1: Plantar pressure parameters, total contact duration (Tc), maximum force (Max F) and maximum pressure (Max P), differences between operated and unoperated sides in AA (red) and TTCA (blue). Negative results represent higher value on the unoperated side and positive results represent higher value on the operated side. ★ $p<0.01$
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Op versus Unop side comparisons for the AA group showed a significant increase in (Tc) in the HL, HM, ML, MM, FL, FC, FM, and TF; significantly higher (Max P) at the HM, FC, and FM as well as significantly higher (Max F) in the FM on the Unop side. All together 12 out of 30 parameters showed significant difference. In stark contrast, the TTCA group only showed one significant difference: longer (Tc) of the FC region on the Unop side. In order to better illustrate the bilateral symmetry based on plantar pressure distribution, Figure 1 represents the mean difference between the two sides in each of the two case groups, values close to zero represent good symmetry.

Comparison between the Op sides of TTCA and AA showed higher values in the TTCA group for the following variables: (Tc) in HL, HM; (Max P) in the HM, MM and FM; (Max F) in the FM. No significant difference was reported between the Unop sides of the two case groups.

Kinematics

The inter-segment ROM results are summarized in Table 3. Comparing to the controls, the Op sides of both TTCA and AA groups showed a significantly reduced ROM at each intersegment in the three planes ($p<0.01$) with an exception of the forefoot-hindfoot segment in the coronal plane for both cases and transverse plane in TTCA. Reduced ROM of the Unop sides of the case groups compared to the controls was observed in the sagittal plane at forefoot-hindfoot, forefoot-shank, and in the transverse plane at forefoot-shank in TTCA and at forefoot-shank in sagittal plane in AA.

The Op versus Unop side comparison showed significant reduction in the motion of the forefoot-hindfoot and forefoot-shank in the sagittal plane and hindfoot-shank and forefoot-shank in the coronal plane and in forefoot-shank in the trasnsverse plane for AA patients, whilst in TTCA patients significant reduction was reported for the hindfoot-shank and forefoot-shank motion in the sagittal plane and forefoot-shank motion in the coronal plane. Furthermore, comparison between the Op sides of the two case groups showed that hindfoot-shank motion of the TTCA patients were significantly reduced in the sagittal plane. No differences were reported between the Unop sides of the two case groups. It can be noted that forefoot-shank motion on the Op side in both case groups were similar, representing similar level of restriction with and without subtalar fusion. This was best illustrated in the sagittal and coronal planes (Figure 2). These graphs also demonstrate the pattern of pathologic motion with the absence of complete plantar flexion and inversion at the end of stance phase for both AA and TTCA Op and Unop as well as the excess of dorsiflexion before push off of the Unop side of both AA and TTCA patients.

Table 3: Median (IQR) of intersegment displacement in sagittal, coronal, and transverse planes

Plane	Inter-segments	TTCA Op	TTCA Unop	AA Op	AA Unop	Control
Sagittal	FF-HF	12.2 (4.3) †	17.8 (3.1) †	10.4 (4.4) † *	19.9 (5.0) *†	26.6 (6.1)
	HF-SH	4.9 (2.2) †*¶	12.8 (5.8) *	9.6 (5.3) †¶	12.2 (5.6)	12.1 (3.8)
	FF-SH	16.4 (2.1) †*	27.7 (5.2) †*	16.9 (5.3) †*	27.1 (4.1) *†	34.2 (4.7)
Coronal	FF-HF	5.3 (2.7)	9.36 (7.1)	5.0 (1.6)	6.5 (2.7)	8.3 (4.4)
	HF-SH	7.4 (2.2) †	8.5 (3.0)	6.7 (2.4) †*	10.6 (2.8) *	10.4 (3.1)
	FF-SH	8.0 (2.0) †*	16.4 (1.8) *	7.2 (1.3) † *	13.5 (2.8) *	15.1 (6.2)
Transverse	FF-HF	5.6 (4.3)	8.4 (3.6)	2.9 (3.2) †	5.9 (2.9)	6.2 (3.4)
	HF-SH	3.3 (1.3) †	8.5 (1.8)	5.8 (2.1) †*	9.75 (4) *	9.3 (3.5)
	FF-SH	5.7 (2.1) †	7.6 (5.3) †	5.5 (2.5) †	10.1 (3.9)	13.9 (5.6)

* Indicates significant difference ($p<0.01$) of Op-Unop comparison. †Represents significant difference ($p<0.01$) compared to control average. ¶ Represents significant difference ($p<0.01$) of TTCA Op and AA Op side comparison

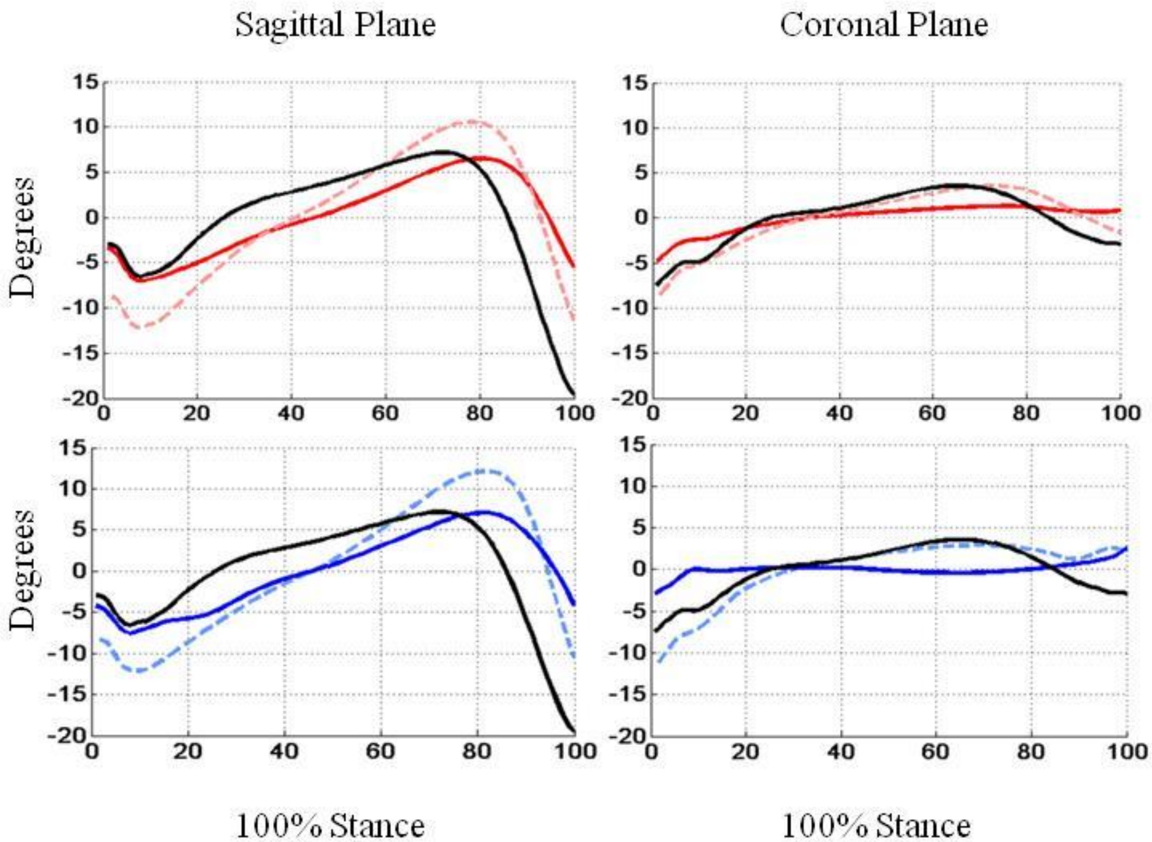

Figure 2: Forefoot-shank segment motion in sagittal and coronal planes. Black solid line represents control, colored solid line represents. Operated side and dashed lines represent Unoperated side. AA (red) and TTCA (blue). Similar levels of restriction of both AA and TTCA Op sides are observed.

Spatiotemporal Parameters

Spatiotemporal parameters results for each group are summarized in Table 4. In comparison with the controls, both Op and Unop sides of each case group showed reduced cadence, prolonged stance phase duration (with the exception of the Op sides), reduced duration of loading phase (with the exception of the Op sides), prolonged duration of foot-flat phase, reduced duration of push-off, shorter stride, lower speed and reduced peak angular velocity ($p<0.01$). The Op versus Unop side comparison showed a reduced duration of stance, a prolonged phase of loading and a reduced peak angular velocity in the AA group, whilst Op side of TTCA patients was associated with reduced duration of stance, a prolonged phase of loading. Comparison between the Op sides of TTCA and AA groups showed no significant difference in any parameter. Similar non significant results were reported when the Unop sides of the two case groups were compared.

Table 4: Median (IQR) of spatiotemporal parameters of gait

Parameters	TTCA Op	TTCA Unop	AA Op	AAUnop	Control
Cadence (steps/min)	90.7 (18.6)†	98.4 (17.1)†	103.7 (16.8)†	105 (17.5)†	122 (12.2)
Stance (GCT)	59.2 (2.4)*	62.6 (1.9)* †	56.8 (2.3) *	61.5 (2.2)*†	57.4 (2.1)
Load (St.%)	12.2 (5.4)*	8.8 (2.6)*†	13.1 (3.5) *	9.8 (2.6) *†	12(4.2)
Foot-flat (St.%)	65.7 (12.0)†	65.7 (11.1)†	62.8 (11.4) †	63.1 (5.7)†	52 (5.1)
Push-off (St.%)	23.9 (7.8)†	26.1 (10.9)†	26.8 (7.5) †	28.8 (4.4)†	36.9 (5.8)
Stride (m)	1.1 (0.2) †	1.1 (0.2)†	1.08 (0.2) †	1.13 (0.2)†	1.26 (0.2)
Speed (m/s)	0.8 (0.3)†	0.9 (0.3)†	0.85 (0.3) †	0.95 (0.2)†	1.3 (0.3)
PAVS (°/s)	321.7 (94)†	363 (92.3)†	336 (70.3)*†	369 (33)*†	412.9 (69.7)

* Indicates significant difference ($p<0.01$) of Op-Unop comparison. †Represents significant difference ($p<0.01$) compared to control average. ¶ Represents significant difference ($p<0.01$) of TTCA Op and AA Op side comparison. GCT%: % of gait cycle time, St.%: % of stance time, PAVS: peak angular velocity.

DISCUSSION

Several studies have assessed gait mechanics following AA [6, 18, 22, 25] however, only one study, by Tenenbaum et al. [24], assessed the same following TTCA. From a solely clinical perspective AA and TTCA have been compared using functional scores reporting good outcome following either surgery [1]. However, biomechanical comparison following AA and TTCA is missing in the literature. Hence, the present study is the first to comprehensively assess and compare gait mechanics following both AA and TTCA as well as additionally assess gait symmetry. A further strength of the study is the assessment protocol, which utilize a multisegment foot model providing a comprehensive bilateral gait profile. Furthermore, the ambulatory gait assessment system used is not lab based and tests the participants in an open environment, providing truly representative data without spatial restriction.

The patients of both case groups were homogeneous in terms of clinical status and demographics, contributing to the lack of bias between the groups. Compared to the controls, our patients were slightly, older and heavier which may be regarded as a weakness of the study. However, the differences between the observed gait of patients and those of the controls were so significant that, older controls are unlikely to have lead to different results. Another limitation could be the relatively small study size. However, comparable previous gait studies included similar number of patients per group [6, 16, 20, 22, 26], and differences in recorded parameters reached reputable levels of significance at $p<0.01$. Missing preoperative data is another limitation of the study, which could have given better insight to each patient's initial level of bilateral symmetry. However, TTCA patients consisted of mostly failed cases of total ankle replacement or combined arthrosis of tibiotalar and subtalar joints and in such cases one could assume that walking would have been painful and that unoperated side loading would likely have been increased to reduce pain.

Overall, gait results in the present study were comparable with those already reported [6, 22, 24-26]. However, kinematics outcome in our controls, especially in the sagittal plane, were reported to be slightly higher than in previous studies [18, 25]. This could be the result of drift error reported in body worn inertial sensors [9, 19, 21]. However, a few degrees of error are suspected due to the external effects on the sensors [19]. A slow walking speed (0.5 m/s) is shown to report less error in comparison to moderate (0.9 m/s) to fast (1.3 m/s) walking speed [19, 21]. Our results also showed some motion around hindfoot-shank intersegment in TTCA, where there should be none. Regardless, the pros of using wearable sensors are more beneficial than the cons.

For AA patients, studies that used a three segment model reported comparable hindfoot motion, while higher forefoot motion 15±5° in comparison to 10.4±4.4° the present study in the sagittal plane [25]. Another study by Wu et al [18] also reported slightly higher motion in all three intersegments in all three planes. Comparing TTCA results with the only related gait study available, Tenenbaum et al [24], difficulty arises, as the study used a single-segment foot model and kinematics results are reported in the sagittal plane only. Their study showed the total range of motion of the ankle in the sagittal plane to be 10.2±1.9° which is significantly less in comparison to this study 16.4±2.1°. In terms of gait symmetry, they reported 24.1±4.3° for the unaffected limb against 27.7±5.2° motion in this study.

The working hypothesis of the study was that gait alteration following TTCA would be greater in comparison to AA and that gait symmetry would also be increased. Gait assessment revealed an altered gait pattern in both Op and Unop sides in each case group when compared to the controls. As such, one can answer the working hypothesis in terms of *pathologic gait* as well as in terms of *gait symmetry*. Furthermore, the hypothesis can be explained from both a quantitative and a qualitative perspective.

Pathologic gait: Quantitative aspects revealed the following number of abnormal parameters: for plantar pressure 7 out of 30 in TTCA against 9 out of 30 in AA Op sides (7/30 TTCA and 11/30 AA Unop sides), for kinematics 7 out of 9 for TTCA against 8 out of 9 for AA Op sides (3/9 TTCA and 2/9 AA Unop sides), for spatiotemporal parameters 6 out of 8 for both TTCA and AA patients Op sides (8/8 for both TTCA and AA Unop sides). These results place TTCA and AA on a similar pathologic level even if a slightly better performance is observed for TTCA in plantar pressure and kinematics. From a qualitative perspective, the AA patients appear to abnormally overload the lateral border of the foot, whilst TTCA patients have a tendency to overload the lateral forefoot. Regarding kinematics, as expected, there is a reduced sagittal hindfoot motion in TTCA compared to AA patients. There is also similar level of stiffness of the foot found in both groups and spatiotemporal data is similarly pathologic for both groups.

Gait symmetry: Quantitative aspects revealed the following number of abnormal parameters: for plantar pressure 1 out of 30 for TTCA patients against 12 out of 30 for AA patients; for kinematics 3 out of 9 for TTCA patients against 5 out of 9 for AA patients; for spatiotemporal parameters 2 out of 8 for TTCA patients against 3 out of 8 for AA patients. This places TTCA and AA patients on a similar level of gait asymmetry regarding kinematics and spatiotemporal parameters, but regarding plantar pressure data, TTCA patients present significantly better gait symmetry. From a qualitative perspective one can observe stronger overload and longer contact duration of the hindfoot, midfoot and forefoot in the Unop side of AA patients which is representative of a limping gait.

In conclusion, the present study is the first to comprehensively assess and compare gait mechanics after TTCA and AA. Findings reject the hypothesis that TTCA is more detrimental for gait mechanics than AA. Furthermore, based on the results of the plantar pressure parameters, TTCA patients appeared to perform better than AA patients, especially in terms of gait symmetry. This study gives interesting insights into the outcomes of both TTCA and AA surgeries and it appears that TTCA is by far not as detrimental in terms of gait mechanics as once thought. Of course, evaluating patients' outcome at a relatively short term follow up, i.e. less than 5 years, does not allow for definitive clinical recommendations. As such, further research should be carried out to determine which pathologic gait parameters are representative of a for long term outcome.

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Bilateral Gait Mechanics in Unilateral End-stage Ankle Osteoarthrosis

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Abstract

Studies have found significantly altered gait parameters followingsurgical treatment of ankle osteoarthrosis, including abnormal gait mechanics in patients' unoperated side. This is usually assumed to be a residual effect of a preoperative adapted gait pattern. However, influence of ankle osteoarthrosisoutcome on the contralateral foot is not well studied.This study,aims to assess bilateral gait mechanics in ankle osteoarthrosis patients to understand the extent of gait alterations.20 participants, including 10 healthyand 10 end-stage ankle osteoarthrosiscases, were assessed using 3-D inertial sensors and pressure insoles. Altogether,48 gait parameters were assessedand compared ($p<0.01$). Comparing the affected and unaffected sides in the case group, 8 out of 48 parameters showed significant difference. Furthermore, in comparison to the controls, affected and unaffected sides showed significant difference in 20 and 14 out of 48 parameters, respectively.Patients with end-stage ankle osteoarthrosis show altered gait parameters on both affected and unaffected sides when compared with controls. However, contrary to previous postoperative assumptions relative gait symmetry exists preoperatively. This suggests that postoperative gait asymmetry followingankle osteoarthrosis is not necessarily a residual effect, but rather a consequence of surgery and orinadequate rehabilitation.

Keywords: Ankle arthritis, gait analysis, plantar pressure, kinematic, gait symmetry

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Introduction

Ankle Osteoarthrosis (AOA) is a chronic progressive degenerative disease which affects the quality of life of patients because of pain and progressing deformity. Among the incidences of osteoarthrosis of weight bearing joints, the AOA is relatively low, in comparison to hip and knee joints, with only 1–4% of the adult population being affected with the disease[1, 2]. Post traumatic and secondary AOA are the most common forms of AOA presented in clinical practice and are seen frequently in the younger aged population[1, 3] in comparison to hip and knee osteoarthrosis[4, 5], hence the impact on a patient's quality of life and work capacity can be severe.

Several surgical options are available for the treatment ofend-stage AOAbased on the severity of the disease and the structures involved. Treatment is inclined towards reducing pain and making the patient as functionally independent as possible. Nonetheless, AOA patients in early adulthood may face a greatly restricted lifestyle.Studies have assessed gait mechanics post ankle surgeries and reported existence of altered gait mechanics on both operated and unoperated sides[3, 6, 7]. An explanation for this alteration is that it is due to residual gait alterations from the preoperative period, where constant pain would have resulted in asymmetrical loading[2, 8]. Studies have assessed AOA patients based on spatiotemporal and kinematic parameters on the affected foot[9, 10], or based on plantar pressure parameters of both affected and unaffected sides [2, 11]. Even so, Horisberger et al did not include a baseline control group to compare with [2]. The study aims to improve understanding of gait mechanics in end-stage AOApatients by assessing all aspects of gait on both the affected and the unaffected sides.

Methods

20 participants were divided into twoage matched groups: 10end-stage AOApatients and 10 healthy controls. Case group consisted of the consecutive patients with isolated post-traumatic

end-stage ankle osteoarthrosis, stages 3 and 4 according to Kellgren and Lawrence, who had not been affected by other pathologies of the lower extremities or spine. The control population consisted of volunteers with no prior history of lower limb or spinal pathology. All participants gave their informed consent and approval of the ethics commission of our University was obtained.Clinical and demographic status of AOApatients is given in Table 1. Clinical assessment included; the American Orthopedic Foot and Ankle Society Score for hindfoot (AOFAS) [12], the Foot and Ankle Ability Measure Score- activity of daily living section (FAAM) [13], along with the general health specific score EQ-5D [14].

Table 1: Demographics of the study population, result in mean (SD)

Demographics and Clinical assessment	AOA	Control
Age	65.8 (8.9)	64.9 (9.1)
BMI	27.6 (3)	25.7 (5.5)
AOFAS-total	48 (18) †	100 (0)
FAAM-ADL	61 (19) †	100 (0)
EQ-5D	0.47 (0.3) †	1 (0)

† represents ($p<0.05$) in comparison to the controls

Gait assessment was performed using an ambulatory pressure insole (Pedar-X, Novel, Germany) and five inertial sensors consisting of 3-D accelerometers and gyroscopes. The sensors were attached to the medial region of both tibias, the posterior aspect of the great tuberosity of the calcaneus between the base of the first and second metatarsals, and on the dorsal region of the proximal phalanx of the first toe. Sensors were connected to two portable data acquisition systems (Physilog, BioAGM, CH). In the case group, each footwas measured separately. Insoles were available in four sizes. The setup, reliability and accuracy of the used technology and assessment protocol have been validated by Rouhani H et al.[15, 16].

Each test started withfunctional calibration of the assessment system, via passive knee movements[17], followed by two walking trials at the natural walking speed along a 50m distance. The procedure was then repeated for the contralateral foot. The first and last three cycles of each trial were discarded to removethe instabilities during the initiation and termination of walking. Subsequently, spatiotemporal, kinematics and plantar pressure parameters were assessed for all gait cycles of each trial. The spatiotemporal parameters assessed include; stance in percentage of gait cycle time (GCT%),cadence (steps/min), inner-stance events [18](load, foot-flat, and push-off phases (stance %)), stride (m), speed(m/s), peak swing speed (°/s) and heel-strike pitch (°) and toe-off pitch (°) angles. Intersegmentrotations during ambulation, were assessed in thesagittal (dorsiflexion/plantarflexion), coronal (inversion/eversion), and transverse (abduction/adduction) planes, for the following intersegments: forefoot-toes, hindfoot-forefoot, shank-hindfoot and shank-forefoot[16].

Plantar pressure parameters were assessed at 10 anatomical sub-regions[7] including; hindfoot-lateral and medial; midfoot- lateral and medial; forefoot- lateral, central and medial; and toes -third toe (third to fifth toe), second toe and first toe. The parameters assessed total contact duration (% stance), maximum pressure (Max P) (kPa), and maximum force (Max F) (% body weight).

The average of each gait parameter for each individual was compared between the AOAaffected and unaffected sides and with the controls, using nonparametric statistical analyses. A Wilcoxon signed-rank test was performed to compare the intraindividual symmetry between the affected and unaffected sides in the AOAgroup and a Wilcoxon rank-sum test for comparing both sides of the case group with controls. The level of significance was $p<0.01$.

Results

The spatiotemporal results are displayed in Table 2. In comparison to the controls, affectedside of the AOAgroup showed a reduced cadence, shorter stride, lower speed, reduced peak swing speed and lower toe-off pitch angle ($p<0.01$). On the other hand, the unaffected side showed reduced cadence, increased foot-flat duration, reduced push-off duration, speed, and peak swing speed ($p<0.01$) in comparison to the controls. Comparingaffected andunaffected sidesno significant difference was reported.

Table 2: Spatiotemporal parameter of gait, result in mean (SD)

Spatiotemporal parameters	AOA Affected side	AOA Unaffected side	Control
Stance (GCT%)	58.6 (2.5)	61.8 (3.8)	58 (2.4)
Cadence (steps/min)	96.9 (15.8) †	98.4 (14.9) †	114.2 (9.5)
Load(St%)	9.6 (3.05)	9.1 (3.1)	11.7 (2.58)
Foot-flat (St%)	61.3 (10.2) †	64.8 (7.2) †	54.2 (3.2)
Push-off (St%)	29.1 (9.3)	26.1 (4.8) †	34.04 (3.86)
Stride (m)	0.99 (0.25) †	1.02 (0.26)	1.25 (0.1)
Speed (m/s)	0.83 (0.3) †	0.86 (0.3) †	1.2 (0.1)
Peak swing speed (°/s)	289.1 (81.2) †	316.7 (69.1) †	389.86 (38.4)
Toe-off pitch angle (°)	55.2 (11.4) †	59.7 (10.7)	70.25 (6.4)
Heel-strike pitch angle(°)	16.6 (5.8)	16.5 (6.9)	20.1 (3.8)

† Comparison to the controls ($p<0.01$), * comparison to unaffected side ($p<0.01$).

Inter-segment displacement results are summarized in Table 3. Comparing to the controls, the affected side of AOAgroup showed a significantly reduced range of motion at all four intersegment in the sagittal planewhile the unaffected side showed difference only in the toe-forefoot intersegment ($p<0.01$). Affected and unaffected sides comparison showed significant difference in the motion of the forefoot-hindfoot and forefoot-shank intersegment in the sagittal plane and forefoot-shank intersegment in the coronal plane ($p<0.01$).

Table 3: Intersegment rotations at sagittal and coronal planes, result in mean (SD)

Movement Planes	Intersegments	AOA affected side	AOA unaffected side	Control
Sagittal	Toes-forefoot	27.6 (9.2) †	32.4 (7.8) †	40.6 (4.9)
	Forefoot-hindfoot	12.3 (3.5) †*	23.7 (7.3)	24.8(6.8)
	Hindfoot-shank	10.4 (3.9) †	14.5 (4.3)	16.1 (3.5)
	Forefoot-shank	15.9 (6.6) †*	24.3 (5.8)	28.9 (6.5)
Coronal	Toes-forefoot	10.1 (3.2)	11.5 (2.9)	13.1 (2.6)
	Forefoot-hindfoot	16.7(7.3)	15.2 (2.9)	11.0 (3.8)
	Hindfoot-shank	15.2 (6.9)	12.1 (3.8)	13.1 (3.6)
	Forefoot-shank	11.7 (3.8) †*	16.5 (4.5)	16.0 (4.2)

† Comparison to the controls ($p<0.01$), * comparison to unaffected side ($p<0.01$).

Plantar pressureresults for 10 sub regions of the foot are given in Table 4. Comparing the AOA affected side to the controls, the following differences were reported; Tc was significantly shorter in the first toe ($p<0.01$) and longer in midfoot lateral and forefoot central subregions, Max F and Max P was significantly lower in the hindfoot medial, first and second toeregions ($p<0.01$) on the affected side. Comparing the AOA unaffected side to the controls, significant difference was found atTc in midfoot lateral, forefoot central, third and first toe regions and Max F at hindfoot lateral, forefoot lateral and first toe regions($p<0.01$). The affected and unaffected side comparison in the case group showed significant differences only in the toe regions; reduced Tcand Max F in first and second toe andreduced Max P in second toe region($p<0.01$) on the affected side.

Table 4: Plantar pressure parameter of gait, result in mean (SD)

Foot segments	Plantar pressure	AOA affectedside	AOA unaffectedside	Control
Hindfootlateral	Tc	56.1 (17)	61.3 (22.8)	49.6 (9.3)
	Max F	22.4 (9.6)	17.8 (6.7)†	28.1 (8.5)
	Max P	82.9 (21.9)	74.98 (26.7)	95.7 (35.8)
Hindfoot medial	Tc	58.2 (17.1)	66.7 (16.8)	63.8 (19.1)
	Max F	27.7 (5.9) †	27.2 (12.9)	42.6 (9.7)
	Max P	97.0 (21.5) †	99.2 (44.5)	139.1 (35)
Midfoot lateral	Tc	59.5 (12.4)†	60.4 (20.8)†	44.8 (15)
	Max F	12.5 (7.9)	11.4 (9.5)	10.5 (5.3)
	Max P	30.6 (13.0)	34.6 (24.3)	27.2 (14.8)
Midfoot medial	Tc	40.1 (17.4)	35.2 (12.7)	28.8 (7.8)
	Max F	5.1 (2.5)	3.4 (2.5)	4.5 (2.7)
	Max P	16.3 (6.0)	12.9 (6.6)	13.7 (5.6)
Forefoot lateral	Tc	87.8 (4.8)	89.2(4.9)	79.8 (14.1)
	Max F	28.6 (12.9)	22.7 (11.5)†	34.2 (9.5)
	Max P	116.9 (41.1)	93.2 (44.4)	106.7 (39.1)
Forefoot central	Tc	84.7 (5.7)†	85.4 (11.5)†	72.3 (13.3)
	Max F	26.3 (7.9)	20.0(11.6)	29.8 (8.6)
	Max P	148.9 (42.3)	109.1 (59.3)	132.9 (29.7)
Forefoot medial	Tc	63.1 (12.3)	65.2 (16.1)	60.7 (16.5)
	Max F	14.1 (7.5)	14.5 (9.1)	18.2 (8.1)
	Max P	73.5 (36.8)	75.3 (39.5)	74.3 (25.6)
Third toe	Tc	30.7 (14.3)	29.4 (9.9)†	18.6 (5.9)
	Max F	2.3 (2.0)	4.2 (1.8)	4.0 (3.2)
	Max P	14.7 (5.9)	21.3 (6.7)	17.6 (6.9)
Second toe	Tc	23.2 (12.6)*	37.7 (6.8)	30.8 (7.7)
	Max F	2.1 (1.5)† *	5.8 (2.5)	5.7(3.6)
	Max P	26.8 (14.0)†*	46.2 (16.9)	37.3 (12.3)
First toe	Tc	20.3 (11.4) †*	48.7 (9.6)†	34.9 (8.3)
	Max F	4.4 (4.4) †*	8.6 (2)†	14.7 (7)
	Max P	37.2 (29.7) †	55.3 (13.9)†	80.8 (26.7)

† Comparison to the controls (p<0.01), * comparison to unaffected side (p<0.01).

Discussion

Altered gait patterns are known to continue even after surgical correction of end-stage AOA[3, 7]. It is widely assumed that this alteration is nothing other than the residual effect of the preoperative walking pattern, usually asymmetrical due to severe pain and or discomfort[2]. However, this study assessed bilateral gait mechanics in end-stage AOApatients and found very littleasymmetry, in comparison to the postoperative outcome following certain ankle surgeries shown in previous publications[6, 7].

Gait pattern of the affected side in the AOApatients, in the present study, were similar to previous studies separately assessing different gait parameters. Among spatiotemporal parameters, reduced stride length, cadence and speed on the affected side were reported in comparison to the controls which are similar to previous studies[8, 10]. However, in contrast to previous studies, the stance phase showed no significant difference in comparison to the controls. Out of the 10 studied spatiotemporal parameters, five showed significant difference forboth affected and unaffected sides in comparison to the controls. Furthermore, the bilateral comparison in AOA group showed good symmetry. This level of symmetry in spatiotemporal parameters is far greater to postoperative outcomes[7]. Moreover, in comparison to the controls several parameters showed significant difference on both operated and unoperated sides after either surgeries representing existence of altered gait mechanics [7].

Kinematic results of the present study showed significant difference in all four inter-segments in the sagittal plane on affected side in comparison to the controls- also observed in previous studies [9, 10].In the coronal plane no difference was reported with the controls on the affected side, confirming to Kozanek e al. [9] but contrary to Khazzam et al [10] where a significant reduction in coronal plane motion on the affected side around the tibia, hindfoot and forefoot was reported.

Lastly, plantar pressure parameter results partially coincide with the study by Horisberger et al 2009[2] which showed significantly low peak pressure (kPa) at hindfoot and the toe regions on the affected side in comparison to the unaffected side. Results show that the three toe subregions of the affected side have both maximum force and pressure presenting significantly lower values in comparison to the unaffected side. However, for the hindfoot subregion, no significant difference between the two sides were reported- following the study by Shih LY et al.[11]. The significantly reduced total contact duration in the hallux subregion on the affected side in comparison to the unaffected side confirms to the study by Horisberger et al [2]. However, followingankle arthrodesis and or total ankle replacement, significant differences were reported in the loading pattern of whole foot and hindfoot, respectively[7]. This suggests that the hindfoot mechanics change after both surgery andtheireffects can be seen even on the unoperated side.

Findings draw attention to the possibly negative impact of ipsilateral ankle surgeries on the contralateral foot. Altered gait mechanics on the unoperated side are seemingly not pre-existing but rather postoperative adapted gait pattern. This may be due to several reasons, such as apprehension, pain, prolonged immobilisation, naturalisation to the postoperative changes, and insufficient rehabilitation. If true, this would mean that such asymmetry could be corrected, if not completely prevented.

Strength of the study is the elaborate assessment of 48 gait parameters in patients with end-stage ankle osteoarthrosis. The gait analysis system utilized is portable and allows to test the patients in an open environment capturing data from several number of consecutive gait cycles instead of just a few within a restricted gait lab environment.The study does have a limitation that is the small population size. Nonetheless, the results presented reached reputable level of significance. Furthermore, comparable gait study by Kozanek M et al, assessedkinematic in AOApatients including similar number of patients and tested only the affected side[9].

In conclusion, patients with end-stage AOA showed significant difference in most gait parameters for both affected and unaffected sides when compared to a control group. However, the gait symmetry is seen to persist following end-stage AOA. Results suggests that the postoperative gait asymmetry may not be influenced by the preoperative gait pattern but rather due to other postoperative reasons including long immobilization phase, pain and adapted walking pattern learned during the early rehabilitation phase. Hence, our findings suggest that, if these alterations can be captured during the rehabilitation phase, the situation could be reverted with proper gait training.

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ORIGINAL ARTICLES

Outcome of ankle arthrodesis and total ankle replacement for ankle arthrosis in terms of gait variability

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Abstract

Background: Higher variability in gait parameters has been reported in patients' with arthrosis of hip and knee joints, leading to dynamic instability and increased risk of falling. Higher variability and gait instability has also been noted to persist months after surgery. Ankle arthrosis is likely similar, but information regarding this is lacking. The purpose of the study was to evaluate gait variability following ankle arthrosis and its surgical treatments, ankle arthrodesis and total ankle replacement.

Methods: Seventy participants, divided into controls, ankle arthrosis, ankle arthrodesis and total ankle replacement, performed gait assessment wearing 3-D inertial sensors through which gait parameters and the variability were compared among groups. Correlations between American Orthopedic Foot and Ankle score and Foot and Ankle Ability Measure score with the gait parameters and their variability were calculated.

Results: All three case groups reported gait variability similar to that of the controls. On the contrary, significant differences ($P < .01$) were reported in several gait parameters when compared to the controls in all case groups. Furthermore, both clinical scores showed little to no correlation with gait variability and a good correlation was reported with gait parameters ($P < .0001$).

Conclusions: The study did not find gait variability to be as reliable compared with gait parameters when assessing the outcome of ankle surgeries. Furthermore, among the gait parameters, walking speed showed a strong correlation with the patients' functional status and is confirmed as an important parameter for ankle arthrosis.

Key words

End stage ankle surgeries, American Orthopaedic Foot and Ankle Score, Foot and Ankle Ability Measure, Outcome evaluation, Gait assessment

1 Introduction

Gait variability describes the fluctuation in gait parameters from stride to stride and has been reported as a quantifiable indicator of walking function [1]. It is expressed by the coefficient of variance (CV %) of spatiotemporal and kinematic parameters of gait. In a dynamic environment, gait variability plays a very important role in providing a stable and good functional mobility with time [1-3]. Hence, some variability in gait parameters is normal and important for stability and quality of movement. However, undesirably high or low variability in gait parameters due to a disturbance in gait regulating systems is not adaptive in nature and leads to instability, increasing the risk of fall [1, 2]. Pathologic joint laxity or restriction leads to compensatory gait patterns with biomechanical deficits, produced by the surrounding structures. This leads to the abnormal increase or decreases in gait variability and reduced postural stability due to the loss of normal sensorimotor integrity [4]. The importance of gait variability in assessing gait stability and regularity has been proven in several studies [5, 6]. Gait variability is also found to be more sensitive in assessing gait instability and fall risk compared to other methods [1, 5].

In hip and knee arthrosis, instability and increased risk of falling has been found to be associated with higher gait variability. As such, it is suggested as a meaningful factor in assessing post-surgical outcome [7-11]. Studies have shown the existence of adapted gait mechanics in end-stage ankle arthrosis patients [12], which are also found to persist even after surgical correction of the disease [13-15]. Altered gait mechanics in ankle arthrosis, as in arthrosis of hip and knee joints, may result in reduced physical activity, gait instabilities and risk of fall [8, 9]. It is, therefore, important to understand the relationship between gait variability and gait stability in ankle arthrosis and after its surgical corrections.

The present study aimed to assess gait variability-a marker of gait instability, gait irregularity and risk of fall in end stage ankle arthrosis and its two common surgical treatments: ankle arthrodesis and total ankle replacement. Participants gait were evaluated using an ambulatory measurement system. The working hypothesis of the study was that the gait parameters and their variability differ significantly in ankle arthrosis, ankle arthrodesis and total ankle replacement in comparison to the controls. Furthermore, the correlation between foot and ankle clinical scores and gait parameters along with their variability was assessed.

2 Material and methods

2.1 Participants

The study included 70 participants divided into four groups: 15 ankle arthrosis, 20 total ankle replacement, 15 ankle arthrodesis, and 20 healthy controls. Patients with unilateral isolated end stage ankle arthrosis, stages 3 and 4 according to Kellgren and Lawrence [16], were included. The operated group consisted of patients with unilateral surgery (ankle arthrodesis or total ankle replacement), with no other pathology of the lower limbs, spine or other factors affecting gait. Inclusion criteria for healthy controls were the absence of any lower limb symptoms or pathology and or other factors affecting gait. All participants gave informed consent. A single surgeon performed both total ankle replacement and ankle arthrodesis surgeries. Patients' selection for ankle arthrodesis or total ankle replacement was nonrandomized and based purely on patients interest. For total ankle replacement surgeries, (Salto, Tornier®, Montbonnot, FR), a mobile bearing implant with three components was used through an anterior approach. For ankle arthrodesis surgeries, internal fixation was performed through a lateral approach using 7.0 cannulated screws (Synthes®, Oberdorf, CH). The mean postoperative follow-up period for the two surgical groups for the gait assessment was 4.7 years (± 2.7 years). Approval of the ethics commission of the University hospital was obtained.

2.2 Assessment method

Clinical assessment was performed using the hindfoot score AOFAS (American Orthopaedic Foot and Ankle Score) [17] and the French version of daily activity sub score of the FAAM (Foot and Ankle Ability Measure) score [18]. The sports section of the FAAM was not included in the statistical comparison because most of our patients from all three groups had left the section incomplete. Gait assessment was performed using 3D inertial sensors, which were connected to an ambulatory data-logger (Physilog®, BioAGM, CH). The sensors (3D accelerometers and gyroscopes) were attached to bony surfaces, minimizing the soft tissue artifact due to muscle contraction. The placement of the sensors was the same as in a previous validation study [15]. Participants were provided with custom made flat sandals that were available in various sizes. Based on the validated protocol, participants walked twice, at their preferred walking speed, along the 50-meter long hospital corridor [19]. Spatiotemporal and angular parameters of gait assessed include: cadence (step/min), stance time (gait cycle time (GCT %)), inner stance event (load, foot-flat and push-off) [20], stride (m), speed (m/sec), peak swing speed (PSS) (˚/sec), toe-off pitch angle (TOP) (˚) and heel-strike pitch angle (HSP) (˚). The affected side was tested for the study groups and randomly selected side for the controls.

2.3 Statistical analysis

For each trial of 50 m, the mean and standard deviation (SD) of each assessed parameter was estimated over all gait cycles after discarding the first three and last three gait cycles. After that, stride-to-stride variability was calculated using the coefficient of variation (CV% = 100 × SD/mean). Shapiro-Wilk test of normality was performed to test if the normal distribution exists in all groups for each assessed parameter. Results showed that most gait parameters and variability parameters were not normally distributed among the groups. Hence, robust non-parametric Wilcoxon rank sum test were performed to compare gait parameters and their variability between all four groups. Correlation between gait parameters and their gait variability with the clinical scores was calculated using Pearson's correlation coefficient. For all statistical analysis, the level of significance was set at $P < .01$ instead of $P < .05$. This is because with multiple comparisons between groups, a lower significance threshold could have a higher probability of false positives. However, for demographic and clinical score comparison the significant level was set at $P < .05$ as the multiple comparisons would not affect the outcome.

3 Results

3.1 Demographics & Clinical score

No significant difference was seen between the three case groups in age and body mass index (BMI). However, all three case groups were on average older and heavier ($P < .05$) compared to the controls. A significantly higher ($P < .01$) AOFAS score was reported in both surgical groups in comparison with the ankle arthrosis group. Furthermore, function sub score were found to be similar in ankle arthrosis and ankle arthrodesis groups. Lastly, the FAAM-ADL sub score showed improvement in both the operative groups in comparison to the ankle arthrosis group. However, the improvement was found to be significant only in total ankle replacement group ($P = .01$) when compared with the ankle arthrosis group (see Table 1). Both the clinical scores showed a significantly reduced functional status in patients of the three case groups in comparison to the controls.

Table 1. Demographics and Clinical Scores of Participants in Control Group and of Patients, mean (SD)

Physical Characteristics	Control	Ankle Arthrosis	Ankle Arthrodesis	Total Ankle Replacement
Age (years)	59.3 (8.9)	65.8(9.8)*	64.2 (9.3)*	63.6 (9.3)*
BMI (Kg/m^2)	24.36 (4.9) $^{\dagger\P\infty}$	29.7 (6.2)*	28.08 (6.4)*	28.72 (4.8)*
Sex	16F/ 4M	10F/ 5M	9F/ 6M	8F/ 12M
AOFAS Total	100 (0) $^{\dagger\P\infty}$	55 (20)$^{*\P\infty}$	70 (11.5)†*	81.5 (20.7) †*
Pain	40(0) $^{\dagger\P\infty}$	20 (20)$^{*\P\infty}$	30 (15)†*	30 (7.5) †*
Function	50 (0) $^{\dagger\P\infty}$	31 (8)$^{*\infty}$	31 (4)$^{*\infty}$	41 (8.7)†*¶
Alignment	10 (0) $^{\dagger\P\infty}$	5 (2.5)$^{*\P\infty}$	10 (0)†*	10 (0)†*
FAAM-ADL	100 (0) $^{\dagger\P\infty}$	61.2 (18.5) $^{*\infty}$	68.75 (17.6)*	79.8 (17.4)*†

Note. *indicated significance difference compared to controls, † represent significant difference compared to ankle arthrosis, ¶ indicates significant difference compared to ankle arthrodesis, $^{\infty}$ represent significant difference compared to total ankle replacement ($P < .05$). AOFAS: American orthopaedic foot and ankle society hindfoot score, FAAM-ADL: Foot and ankle ability measure score - activity of daily living section.

3.2 Spatiotemporal and angular parameters of gait

Results of gait parameters for the four groups are given in Table 2. Comparing with the controls, the ankle arthrosis group showed significantly reduced cadence, load, push-off, stride, speed, PSS, HSP, TOP (P < .01) and increased foot-flat duration (P < .01). Similarly, ankle arthrodesis group showed significantly reduced cadence, push-off, stride, speed, peak swing speed, toe-off pitch angle (P < .01) and increased foot-flat duration (P < .01). Whilst, total ankle replacement group showed significantly reduced cadence, push-off, speed, TOP (P < .01) and increased foot-flat duration (P < .01).

Comparing with the AOA group, no significant difference was seen in the ankle arthrodesis group. However, total ankle replacement group showed a significantly increased cadence, stride, speed, peak swing speed, heel-strike pitch angle and toe-off pitch angle (P < .01). Lastly, a comparison between total ankle replacement and ankle arthrodesis group showed a significantly increased cadence, stride, speed, peak swing speed and reduced toe-off pitch angle (P < .01).

Table 2. Parameters of Gait in Controls and Patients, mean (SD)

Gait Parameters	Control	Ankle Arthrosis	Ankle Arthrodesis	Total Ankle Replacement
Cadence	117.6 (1.3)$^{\dagger\P\infty}$	96.56 (16.5)$^{*\infty}$	100.1 (12.1)$^{*\infty}$	109.3 (9.4)†¶
Stance (GCT %)	58.47 (1.99)	58.8 (2.4)	58.8 (2.7)	58.9 (2.2)
Load (St %)	12.1 (3.3)†	9.7 (2.9)*	11.9 (4.4)	11.3 (2.4)
Foot-flat (St %)	52.5 (5.9)$^{\dagger\P\infty}$	60.8 (10.2)*	61.1 (8.5)*	57.7 (6.1)*
Push-off (St %)	35.5 (4.87)$^{\dagger\P\infty}$	29.6 (9.6)*	26.9 (5.6)*	30.98 (6.4)*
Stride (m)	1.3 (0.1)†¶	1.04 (0.2)$^{*\infty}$	1.04 (0.18)$^{*\infty}$	1.17 (0.12)†¶
Speed (m/s)	1.3(0.18)$^{\dagger\P\infty}$	0.84 (0.27)$^{*\infty}$	0.87 (0.23)$^{*\infty}$	1.08 (0.2)*†¶
PSS (˚/s)	407.5 (52.7)†¶	290.7 (73.7)$^{*\infty}$	306.4 (47.4)$^{*\infty}$	372.1 (53.7)†¶
HSP (˚)	20.48 (4.05)†	16.7 (5.2)$^{*\infty}$	19 (5.4)	20 (4.4)†
TOP (˚)	-74.7 (7.6)$^{\dagger\P\infty}$	-55.1 (10.2)$^{*\infty}$	-53.5 (6.9)$^{*\infty}$	-63.5 (8.6)*†¶

Note. *indicated significance difference compared to controls, † represent significant difference compared to ankle arthrosis, ¶ indicates significant difference compared to ankle arthrodesis, $^{\infty}$ represent significant difference compared to total ankle replacement (P < .01). PSS: peak swing speed, HSP: heel-strike pitch angle, TOP: toe-off pitch angle.

3.3 Variability in parameters of gait

Results of gait parameter variability are given in Table 3.

Table 3. Stride to Stride Variability (expressed by CV% (100 × std/mean)) of Gait Parameter in Controls and Patients, mean (SD)

Gait Parameter variability	Control	Ankle Arthrosis	Ankle Arthrodesis	Total Ankle Replacement
Cadence	3.2 (1.1) †¶	4.3(2.1)*	4.1 (1.3) *	3.4(1.0)
Stance	2.8 (1.1) †¶	3.8 (2.0)$^{*\infty}$	3.3 (0.9)*	2.9 (1.2) †
Load	11.0 (3.1)	13.2 (6.5)	13.1 (5.5)	12.2 (4.9)
Foot-flat	6.7 (2.4) $^{\infty}$	6.3 (4.7)	5.6 (2.1)	5.68 (3.5) *
Push-off	8.5 (2.4)	13.1 (8.1)	9.3 (4.0)	8.9 (4.7)
Stride	10.2 (2.5)	11.5 (4.4)	11.3 (3.36)	12.2 (2.7)
Speed	11.7 (2.1)	13.1 (4.6)	12 (2.4)	12.3 (2.5)
PSS	9.6 (3.5)	11.3 (2.8)	10.6 (3.2)	10.2 (1.8)
HSP	14.8 3.3)	18.2 (9.5)	15.4 (5.8)	14.9 (3.2)
TOP	10.3 (3.7)	12.3 (3.7)	11.1 (3.3)	10.7 (2.6)

Note. *indicated significance difference compared to controls, † represent significant difference compared to ankle arthrosis, ¶ indicates significant difference compared to ankle arthrodesis, $^{\infty}$ represent significant difference compared to total ankle replacement (P < .01). PSS: peak swing speed, HSP: heel-strike pitch angle, TOP: toe-off pitch angle.

Compared to the controls gait variability was found to be significantly high in only cadence and stance in ankle arthrosis and ankle arthrodesis group ($P < .01$), whilst in the total ankle replacement group a significantly reduced variability was reported only in foot-flat parameter. No significant difference was reported between the variability of ankle arthrosis and ankle arthrodesis group, however, the total ankle replacement group showed significantly low variability in comparison to ankle arthrosis in only the stance phase. Comparison between the two surgical groups showed no significant difference in gait variability. Furthermore, gender comparison was made because of the unequal distribution of males and females in each group, however, results showed no significant difference in the gait parameters or their variability.

3.4 Correlation

Results reported a strong correlation between AOFAS score and most gait parameters ($P < .0001$) including cadence, push-off, stride, peak swing speed, toe-off pitch angle and speed (see Figure 1a), however, with respect to the variability in gait parameters a weak to negligible correlation was reported (see Figure 1b). Similarly, with FAAM score, gait parameters reported a strong correlation in most gait parameters including cadence, foot-flat, push-off, stride, PSS, TOP, HSP and speed ($P < .0001$) (see Figure 1a), however, in relation to the variability only foot-flat showed above 30% of correlation (see Figure 1b). For a detailed understanding of the effect of demographics on gait variability, the correlation between gait variability and age, BMI was also assessed. No significant correlation was seen between age, BMI and gait parameters along with their variability. Lastly, as patients walked in their preferred walking speed which differs significantly among groups, the correlation between walking speed and other gait parameters along with their variability was assessed. The results showed moderate to strong correlation ($P < .0001$) with most parameters except stance and load. While in relation to the variability in the parameters, walking speed showed weak to moderate correlation (see Figure 1c).

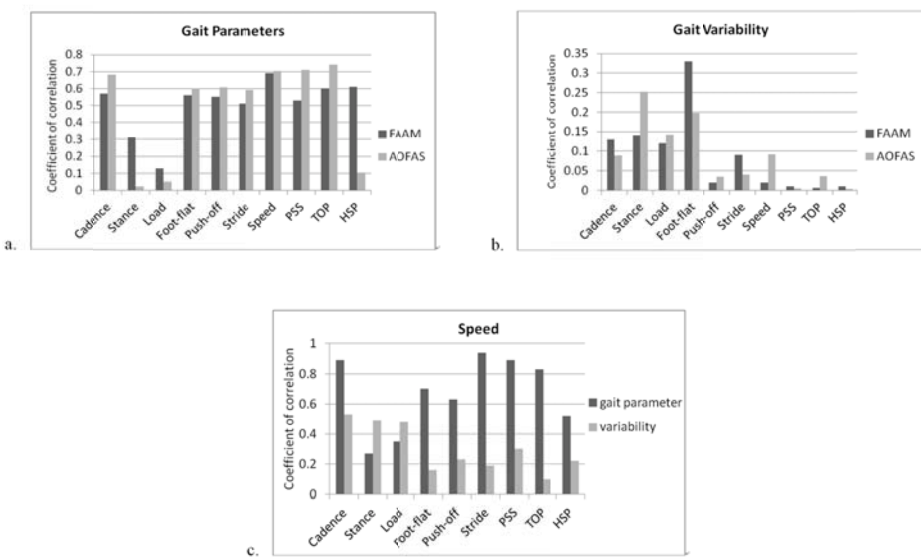

Figure 1. (a) Correlation between AOFAS and FAAM with the gait parameters, (b) Correlation between AOFAS and FAAM with the variability in gait parameters, (c) Correlation between speed and the gait parameters along with the gait variability.

4 Discussion

Studies have shown that dynamic instability can be associated with increased gait variability in patients with various medical conditions, including arthrosis of weight bearing joints like hip and knee, leading to an increased risk of fall [5, 9, 21, 22]. However, the extent of gait variability has not been assessed in ankle arthrosis and its surgical treatments. The study aimed to assess the variability in gait parameters in ankle arthrosis, ankle arthrodesis and total ankle replacement patients. The working hypothesis of the study was that the gait variability differs significantly in ankle arthrosis, ankle arthrodesis and total ankle replacement groups in comparison to the healthy controls. The study, however, did not report much difference in variability between the controls and the three case groups. These results gave a contrasting outcome in comparison to the studies assessing variability in arthrosis of hip and knee joints where the variability was reported to be higher in comparison to the controls [8, 9].

Comparing the variability in ten gait parameters between the controls and the three case groups, significant differences were reported for ankle arthrosis and ankle arthrodesis in only 2 out of 10 parameters and for total ankle replacement one out of 10 parameters. In contrast, comparing the gait parameters between the controls and the case groups reported significant differences in ankle arthrosis (9/10 gait parameters), ankle arthrodesis (7/10 gait parameters) and total ankle replacement (5/10 gait parameters) groups. Furthermore comparing variability between the ankle arthrosis group and the two surgical groups' significant difference was reported in only stance variability in total ankle replacement group, whilst gait parameter comparison showed significant difference in 6 out of 10 parameters in total ankle replacement group. Lastly, the comparison between the two surgical groups showed no difference in variability, whilst in gait parameters 5 out of 10 showed significant difference. As such, the study rejects the null hypothesis that gait variability is abnormally high following ankle arthrosis surgical treatments; ankle arthrodesis and total ankle replacement, in comparison to the healthy controls and as well as among each other.

In our study, the AOFAS and FAAM score results, representing the functional status of the patients, showed consistent results with previous studies [13, 15, 23, 24]. A moderate to strong correlation was reported between both the clinical scores and the gait parameters in comparison to their variability. This suggests that the gait parameters relates better with the clinical status of the patient than their variability. On the contrary, the clinical score for knee had shown a strong correlation with the variability of knee motion in severe knee arthrosis [9]. No clear correlation was seen between age and gait parameters and or variability. The reason could be the patients' age (average 65 years), which is considered relatively early for the initiation of the age related general neuromuscular deterioration [3, 5]. Furthermore, BMI also showed weak correlation with the gait variability, similar to the previous study assessing gait variability in knee arthrosis [9].

Arthrosis of hip and knee joints is mostly due to idiopathic degeneration and tends to appear at an older age in comparison to ankle arthrosis, 70% of cases have a post-traumatic origin and most patients develop the disease at a relatively young age [23]. Elderly patients along with the existing insufficient neuromuscular control due to hip or knee degeneration may be the reason behind the high incidence of fall during the early postoperative phase [7]. Furthermore, the major postural muscles of the lower limbs including quadriceps, gluteus, and hamstrings are affected (wasting and or compensatory over activity) with arthrosis of knee and hip joints [25-27], affecting the balance and increasing the risk of fall. Muscles affected significantly in end stage ankle arthrosis include medial soleus and only fatty degeneration was reported in other muscles [28]. This may be the reason postural stability remains preserved in ankle arthrosis as well as why gait variability parameters are not as important in ankle arthrosis as they are in arthrosis of other weight bearing joints.

Strength of the study is the large cohort size, including ankle arthrosis, ankle arthrodesis and total ankle replacement patients, which revealed more precise results of comparison between the four study groups. The ambulatory gait analysis system used in the study also allowed measurement of several strides at a time, in an open environment-necessary for an accurate assessment of gait variability [3]. The study, however, also has some limitations. In FAAM, only ADL section of the score was utilized, instead of the complete score (ADL + sports). However, the purpose of the score was to find the extent of the correlation between functional status and gait variability. The results reported utilization of the FAAM-ADL was also conclusive irrespective of the inclusion of the sports section results. It is important to note that one cannot assume causality of the defined outcome of either of the surgical groups based purely on surgical intervention due to a lack of pre-operative data. On average there was a difference in demographics of controls compared to the study groups but our results showed no effect of age or BMI on the outcome of variability. Furthermore, the difference of 5 years between the controls and the case groups would not affect the gait results so significantly as to alter the outcome, and hence, this was considered to have little impact on the conclusions.

In conclusion, the study found that, unlike in hip and knee joint problems, gait variability is not an important parameter as compared to other parameters of gait for ankle joint pathologies. The study found that gait variability in ankle arthrosis, ankle arthrodesis and total ankle replacement patients were comparable to controls. However, gait parameters in all three case groups were found to be significantly different. As a result, the study found no additional information in patients' status utilizing gait variability parameters. The study, therefore, concludes that there is no evidence for basing the outcome assessment of an ankle arthrosis surgery on gait variability.

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Qualitative Analysis of Foot Intersegment Coordination in the Sagittal Plane Following Surgery for End-stage Ankle Osteoarthrosis

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Abstract

Today, ankle joint kinematic assessment gives important information regarding the freedom of motion. It does not, however, provide information regarding intersegment coordination. This study aimed to determine whether or not intersegment coordination can provide valuable, otherwise missed information in relation to kinematic alterations of the ankle joint. The study consisted of 40 participants, including 12 total ankle replacement (TAR) patients, 12 ankle arthrodesis (AA) patients and 16 controls. Gait assessment was carried out wearing 3-D inertial sensors. Intersegment coordination was determined by calculation of the continuous relative phase (CRP) between foot intersegments. CRP analysis found useful information regarding the magnitude and directionality of segment motion throughout the gait cycle, with AA patients reporting an altered coordination pattern for all three intersegments, forefoot-hindfoot, hindfoot-shank and forefoot-shank, and TAR patients showing alterations in the hindfoot-shank intersegment. Results show that assessment of intersegment coordination can provide further information, otherwise missed by general kinematic assessment, which could be used to optimize patient rehabilitation. Furthermore, the study showed that such information could be used to compare surgical outcomes. As a result, the study concludes that the inclusion of intersegment coordination assessment could be beneficial in clinical practice.

Keywords: Kinematics, ankle arthrodesis, total ankle replacement, continuous relative phase

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Introduction

In foot and ankle research, gait analysis has played an important role in understanding alterations in gait mechanics for various foot and ankle pathologies. Gait analysis gives information on joint kinematic, allowing one to understand the extent of a patient's mobility. Conventional foot and ankle kinematic assessment portrays the whole foot as a single rigid body, [1, 2] however for a structure with multiple articulations, a single segment models have been found to be less accurate. As a result, several multi-segment foot models were developed to attain detailed information on individual joint rotation. [3-7]

Multi-segment foot models assess joint rotation based on the movement between the two segments, hence were more accurate in assessing the amount of movement at different foot regions in comparison to the single segment model. [8-10] However, this method does not explain the relative action of one segment with respect to the other to achieve the defined movement at a joint at any particular phase of the gait cycle. [11] Knowing the complex anatomy of the foot and ankle joints, along with the available surgical options where the outcome consists of different levels of joint restrictions, the inter-segment coordination quantification would be an interesting method to understand the adaptation and compensation made by different foot segments. The relative phase dynamics helps to assess the inter-segment coordination by utilizing angular displacements and angular velocities of the segments surrounding the joint. [12] Inter-segment coordination has been studied for various sports injuries [13, 14] as well as for hip and knee joint pathologies, [12, 15] but research relating to degenerative diseases of the ankle joint is relatively sparse.

The continuous relative phase (CRP) has been shown to be a reliable tool in characterizing inter-segment coordination based on the phase plane portraits of the distal and proximal segments. [12-14] CRP may therefore be an interesting parameter in assessing the clinical status of the ankle joint after the surgical correction. The aim of the study is to find whether or not inter-segment coordination adds beneficial information which is missed by commonly used kinematic assessments. To achieve this, joint displacement and inter-segment coordination were assessed utilizing a validated measurement system (3-D inertial sensors) and protocol. The segments studied include, forefoot (FF), hindfoot (HF) and shank (SH) for the two most commonly used surgical treatments for end-stage osteoarthrosis of ankle joint- ankle arthrodesis (AA) and total ankle replacement (TAR).

Materials and methods

Participants

This is a retrospective cohort study, with a level of evidence III. The study consisted of three groups: 12 AA patients, 12 TAR patients and 16 healthy controls, totaling 40 participants. Only patients with isolated post-traumatic end-stage osteoarthrosis, who had undergone isolated AA or TAR, between 2003 and 2013, were evaluated. All surgeries were performed by the senior author in the University Hospital's Orthopedic Department. The mean postoperative follow-up period was 4.7 (±2.7) years for AA and TAR patients. Patients were excluded if they were affected by other pathologies of the spine and or lower extremities. Control group inclusion criteria included no prior history of any foot and ankle pathology and or any previous surgeries or trauma of lower limbs which may have affected their gait. All participants gave their informed consent. Approval of the ethics commission of the University was obtained.

2.2 Measurement system and protocol

Gait assessment was performed using inertial sensors consisting of 3-D accelerometers and gyroscopes, in conjunction with the validated protocol. [16] The sensors were attached to the medial aspect of the tibia, at the posterior of the greater tuberosity of the calcaneus and between the base of the first and second metatarsals. These bony anatomical landmarks were chosen to minimize soft tissue instabilities. Sensors were connected to a portable data acquisition system (Physilog®, BioAGM, CH) and data was recorded with a frequency of 200Hz. [16] Custom sandals were given to each participants for optimal placement of sensors. Following the preparation of each participant, functional calibration was performed, [17, 16] after which the participants walked 50m along the hospital corridor twice at their natural pace. For the case group, both operative (Op) and unoperated (Unop) sides were tested. Note that the test retest reliability of the utilized gait assessment method and protocol has both been thoroughly substantiated. [16, 18]

Data Analysis

Kinematic data was measured for 100% of the gait cycle in the sagittal plane. Angular velocity and relative angles were calculated based on the joint coordinate system. [16] For a detailed assessment, stance and swing phases of the gait cycle were then subdivided into: initial contact (IC), loading response (LR), mid-stance (MSt), terminal-stance (TSt), pre-swing (PSw) in the stance phase and initial-swing (ISw), mid-swing (MSw) and terminal-swing (TSw) in the swing phase [19]. Phase plane portraits were created for each participant by plotting the angular velocity (ω) against angular displacement (θ) for all three segments. Phase plane portrait helps one to evaluate gait variation. [20] Furthermore, phase angles (ϕ) were calculated for each segment as $\phi = \tan^{-1}(\omega / \theta)$. Finally, CRP of all three intersegment pairs was calculated by subtracting the phase angle of the distal segment from that of the proximal segment. An illustration of CRP calculation for one intersegment is given in Figure 1.

For CRP calculation, there is a difference in opinion regarding normalization of the phase angle data [13, 21, 22] and several methods have been reported to normalize the phase portraits with uncertain conclusions. [23, 24] In this study, the phase plane portrait was not normalized due to ambiguity in the literature. The sole purpose behind the phase plane portrait normalization is to produce the scalar multiple of the original data such that the amplitude difference can be negated. [22] It is also reported that CRP is not affected by differences in amplitude between segments due to the inverse tangent function removing amplitude differences. [22] A study by Worster et al [25] reported an undesired induced noise from the alterations made by the normalization of the data and supported the above findings of keeping the original phase plane portrait.

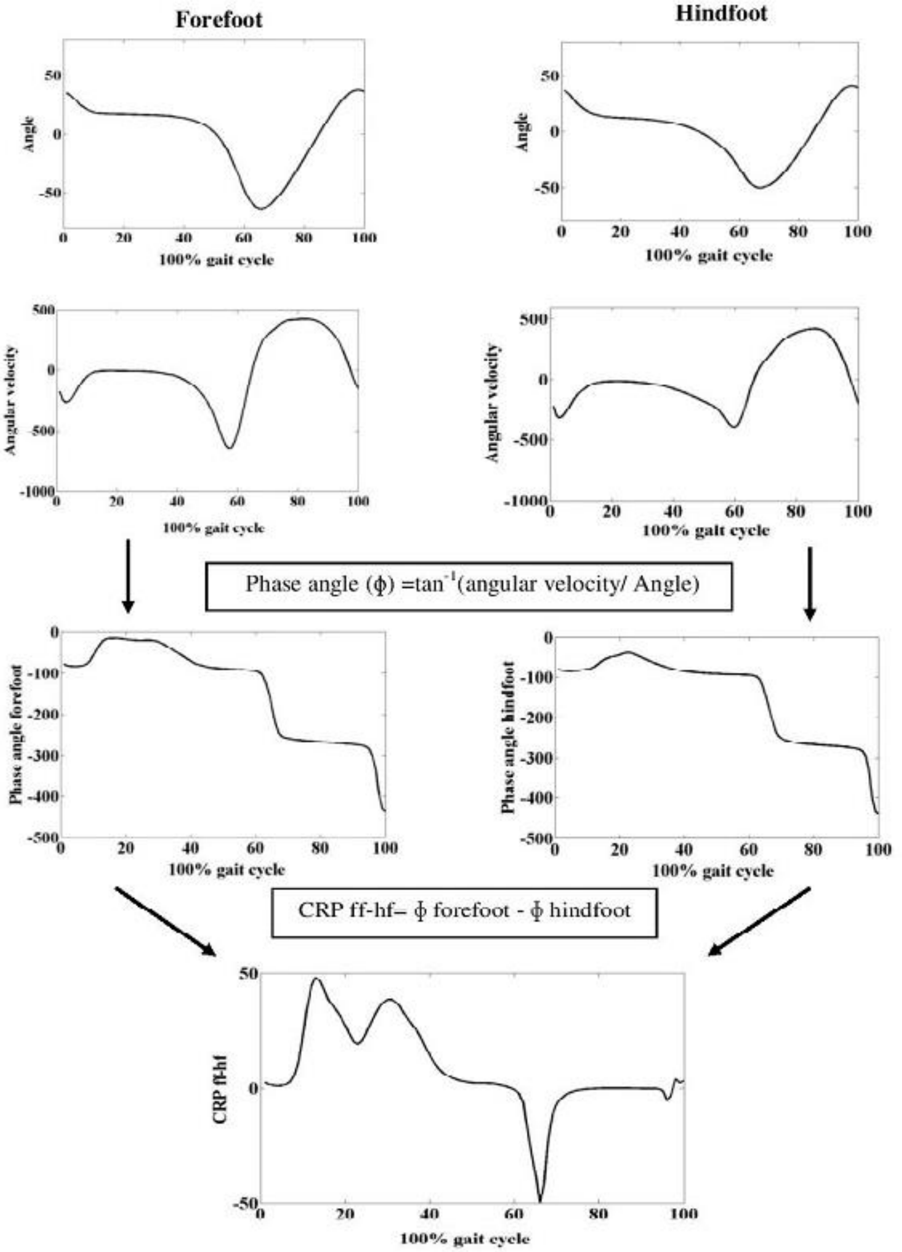

Figure 1: Illustration of continuous relative phase (CRP) calculation using forefoot (FF) and hindfoot (HF) data from the control group.

To characterize the inter-segment coordination maximum peaks, both positive and negative, were calculated at the sub-phases of the gait cycle. This helped to evaluate which of the two segments, distal or proximal, led the movement during the stance and swing phases of the gait cycle. Positive peaks represent that the distal segment dominates movement and vice versa. Finally, mean absolute relative phase (MARP) was calculated in accordance with the previous publication.[26] MARP calculates the mean absolute value of the total CRP curve points in each gait cycle, such that the two segments are moving in close relation to each other if the value is close to zero.

Statistical analysis

Range of motion (ROM), MARP and maximum and minimum CRP peaks, were calculated for each gait cycle. Coefficient of multiple correlations (CMC) was also calculated for each of the three CRP inter-segment pairs for all groups. The strength of the CMC was considered strong at r=0.9, moderate at r=0.5 and weak at r=0.25.[27] Analysis of variance (ANOVA) post hoc Wilcoxon rank sum and Wilcoxon signed rank tests were performed between groups ($p<0.05$).

Results

Intersegment coordination

Evaluation of the CRP curves found various peak patterns in each of the three intersegments (figure 2). Forefoot-hindfoot intersegment, when comparing to the controls showed AA patients have significantly low peaks during the ISw-MSw phase in both Op and Unop sides as well as a significantly large peak during LR-MSt for the Unop side ($p<0.05$). This represents a reduction in hindfoot rotation for both sides of the AA group during the early swing phase and an increased forefoot rotation on the Unop side during the early to mid stance phase. Such an over activity at the forefoot may be detrimental in long run. In contrast, TAR patients reported no significant difference in their intersegment coordination pattern when compared to the controls (Table 1a). Op to Unop side comparison showed significant difference in the peak at the LR-MSt phase for AA patients, representing a bilateral asymmetry in the early to mid stance phase, but again, no difference for TAR patients. Furthermore calculating the MARP, the Unop forefoot-hindfoot intersegment of AA patients showed significantly large values in comparison to the controls and to the Op side, this is likely due to the increased rotation at the forefoot segment.

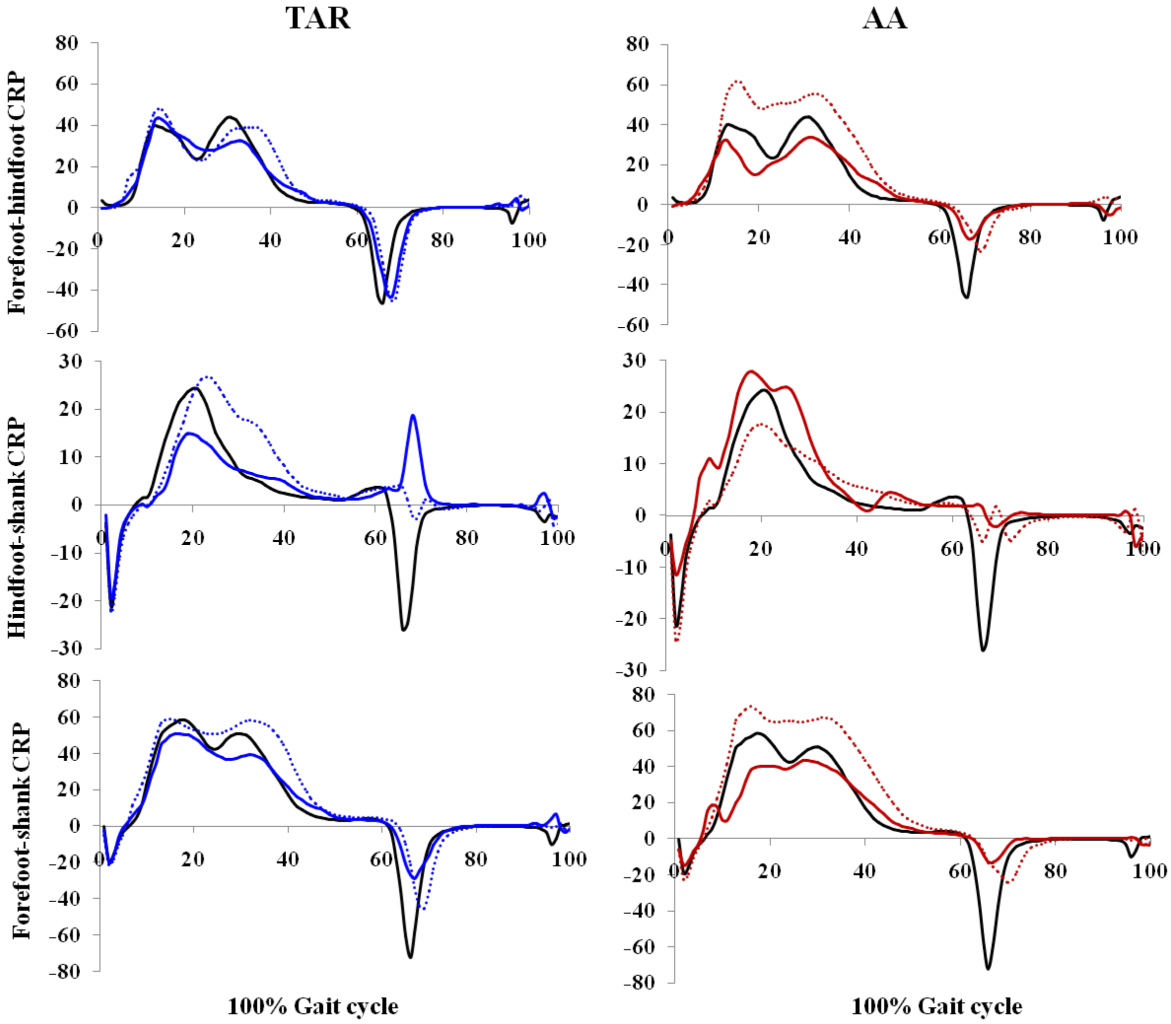

Figure 2: CRP curves at the three inter-segments in sagittal plane; black line represents controls, bold line represents operated side and dot line represent unoperated side

Looking at the hindfoot-shank intersegment, in contrast to the controls little to no peak was reported during the ISw-MSw phase for both Op and Unop sides of AA patients (Table 1b). TAR patients showed similar results for the Unop side, however a comparable peak magnitude was found in their

Op sides, but in the opposite direction. This would hint at a significant hindfoot rotation, rather than shank. Furthermore, during the LR-TSt phase, a significantly low peak is reported for the Op side of TAR patients when compared with the controls, which could be as a result of the low range of motion reported for the hindfoot-shank intersegment. Such differences suggest that, even though TAR operation preserves some motion in the tibiotalar joint it is still not comparable to the controls. Op to Unop side comparison reported similar results for both case groups, with a significant difference being seen in the peak of the IC-LR phase. In the Op side of TAR patients, a reduced hindfoot rotation is observed, while the Unop side showed normal rotation, but for a longer period of the phase. While in AA patients, a large hindfoot rotation was reported on the Op side which is similar to the controls in terms of magnitude but the coordination pattern is relatively uneven. The hindfoot-shank intersegment MARP was found to be low for Op side of TAR patients in comparison to the controls and the Unop side due to the reduced hindfoot rotation throughout the stance phase. Furthermore, AA Op side also reports a significantly low MARP in comparison to the controls, which is likely due to the reduced shank rotation during the swing phase. Note that both surgeries report a restriction of movement as well as altered coordination strategy for the hindfoot-shank intersegment. This can be explained by the fused tibiotalar joint of AA patients and that tibiotalar motion is only partially preserved in TAR patients. Looking at the forefoot-shank intersegment, when compared to the controls, significantly reduced peak magnitudes were observed, during the MSt-TSt and ISw-MSw phases for the Op sides of both case as well as during the ISw-MSw phase for the Unop side of AA (Table 1c). Furthermore, AA patients show an intersegment coordination pattern which appears different in comparison to the controls for the Op side, and, again the Unop side show a significantly large forefoot rotation as observed in the forefoot-hindfoot intersegment. For the Op to Unop side comparison, AA patients showed significantly different peaks during the LR-MSt and MSt-TSt phases, likely due to the over activity of the forefoot segment on the Unop side.

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Table 1a: Max peak in CRP curve at 3 sub-phases of the gait cycle in forefoot-hindfoot segment, mean (SD)

Gait Phases	CON	TAR Op	TAR Unop	AA Op	AAUnop	Group p value
LR-MSt	40.8 (20)	50.5 (23.1)	58.1 (24.4)	37.5 (23.5) ¶	68.98 (26.8)*	0.2
MSt-TSt	57 (20.6)	42.8 (14.5)	47.1 (20.2)	50.9 (24.5)	70.9 (17.1)	0.79
ISw-MSw	-58.9 (23.6)	-60.2 (19.28) †	-58.9 (20.9)	-30.5 (19.9)*	-37.6 (25.1)*	0.05

Table 1b: Max peak in CRP curve at 3 sub-phases of the gait cycle in hindfoot-shank segment, mean (SD)

Gait Phases	CON	TAR Op	TAR Unop	AA Op	AAUnop	Group p value
IC-LR	-19.5 (11.3)	-12.3 (9.7) ¶	-20.8 (13.1)	-13.1 (9.3) ¶	-19.8 (13)	<0.001
LR- TSt	29.9 (11.2)	17.7 (11.2)*	35.9 (19.7)	25.7 (17.7)	26.3 (10)	<0.001
ISw-MSw	-39.3 (14.7)	-4.9 (10.2)*	-10.6 (10.7)*	-6.6 (8.9)*	-15.8 (15.9)*	<0.001

Table 1c: Max peak in CRP curve at 3 sub-phases of the gait cycle in forefoot-shank segment, mean (SD)

Gait Phases	CON	TAR Op	TAR Unop	AA Op	AA Unop	Group p value
IC-LR	-17.5 (10.7)	-12.7 (13.3)	-22.7 (14)	-12.3 (6.8)	-19 (11.6)	<0.001
LR-MSt	59 (12)	57.6 (18.3)	65.4 (18.7)	43.5 (24.3) ¶	73.8 (24.8)	0.58
MSt- TSt	68.7 (20.3)	52.2 (16.6) *	65.8 (22.4)	50.2 (22.8) * ¶	76.8 (11.6)	0.99
ISw-MSw	-71.8 (18.4)	-49 (18.9)* †	-56.7 (23.9)	-22.8(17.6)*	-48.3 (21)*	0.16

Initial contact (TC), loading response (LR), Mid Stance (MSt), Initial Push-off (IP), initial swing (ISw), mid-swing (MSw). * represents difference in comparison with controls, † represent significant difference between AA and TAR and ¶ represent significant difference between Op and Unop sides (p<0.05)

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In contrast, TAR patients had generally good bilateral coordination symmetry. Comparing the Op sides of both case groups, TAR patients showed a significantly large peak during the ISw-TSw phase, as a result of better shank mobility. The forefoot-shank intersegment MARP reports a significantly large value for the AA Unop side in comparison to both the controls as well as the Op side; this is again due to the increased activity of the forefoot, as seen in forefoot-hindfoot intersegment. In contrast, the Op side of both case groups reported a low MARP, representing an overall reduction in mobility (Table 2).

Lastly, the CMC for forefoot-hindfoot, hindfoot-shank and forefoot-shank CRP curves was found to be 0.95, 0.8 and 0.98, respectively, indicating comparable inter-joint coordination patterns between each group.

Table2: Mean Absolute Relative Phase, mean (SD)

Intersegments CRP	**CON**	**TAR Op**	**TAR Unop**	**AA Op**	**AAUnop**	**Group p value**
Forefoot-hindfoot	15.5 (3.5)	14.9 (4.2)	16.7 (4.2)	14.7 (5.8) ¶	21.6 (7.0) *	<0.0001
Hindfoot-shank	7.1 (2.3)	5.2 (1.6) *¶	7.6 (2.3)	5.0 (2.1) *	6.5 (2.1)	<0.0001
Forefoot Shank	20.6 (3.8)	16.6 (3.9) *	22.3 (3.7)	14.4 (7.6) * ¶	27.8 (10.2) *	<0.001

* represents difference in comparison with controls, † represent significant difference between AA and TAR and ¶ represent significant difference between Op and Unop sides ($p<0.05$)

Intersegment displacement

The mean joint angular displacement results, based on inter-segment rotations, are given in Table 3. Figure 3 represent the division of motion between dorsiflexion and plantarflexion at different phases of the gait cycle. In comparison to the controls, significant differences were reported on the Op sides of both AA and TAR patients for hindfoot-shank and forefoot-shank intersegments as well as the forefoot-hindfoot for AA. Op to Unop side comparison showed a significant difference in all three intersegments for AA patients. However, TAR patients only reported a difference in the forefoot-shank intersegment. Comparison between the Op sides of the two case groups showed significant differences in forefoot-hindfoot and forefoot-shank intersegments.

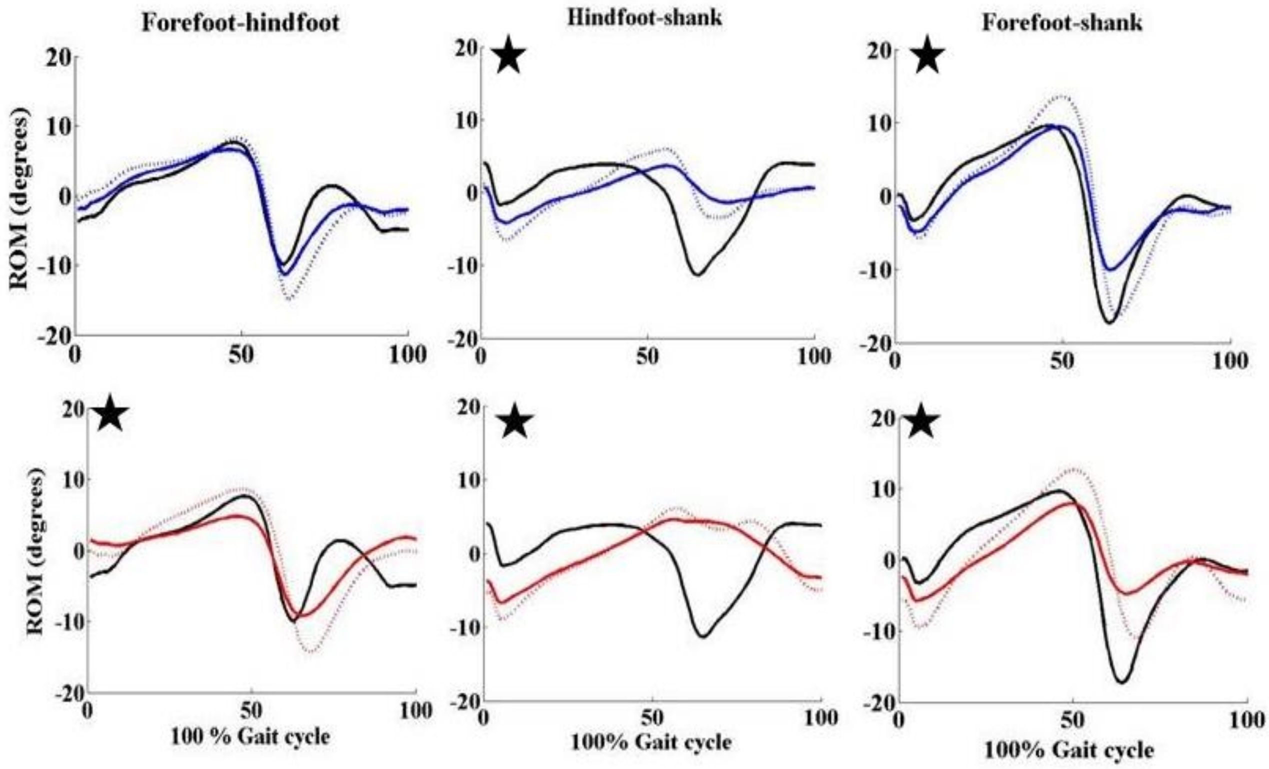

Figure 3: Graph presenting dorsi and plantar flexion movement in the sagittal plane over 100% of the gait cycle. ★ represents significant difference to the controls.

Table 3: Angular displacement, in the sagittal plane, for three intersegments. Mean (SD)

Joint coordinate	CON	TAR Op	TAR Unop	AA Op	AA Unop	Group p value
forefoot-hindfoot	23.7 (6.3)	20.3 (6.2) †	23.9 (6.1)	10.3 (3.5) * ¶	20.3 (3.2)	<0.001
hindfoot-shank	12.5 (3.6)	9.7 (3.6) *	13.4 (4.3)	8.6 (3.4) * ¶	12.3 (3.1)	0.004
forefoot-shank	29.2(7.5)	22.5 (5.9) * †¶	28.6 (4.7)	16.1 (4.0) * ¶	28 (2.9)	<0.001

* represents difference in comparison with controls, † represent significant difference between AA and TAR and ¶ represent significant difference between Op and Unop sides (p<0.05)

Discussion

This study aimed to introduce intersegment coordination when assessing the kinematics of the ankle joint, utilizing CRP as it has generally not been studied for foot and ankle segments joint surgeries. The purpose of the study was not to compare the outcome of the two surgeries but to see if CRP method for inter-segment coordination assessment could be of any benefit for clinical population with different ankle surgeries. The study provided baseline intersegment coordination patterns for the controls and then compared them with the results of AA and TAR patients. Results show that the use of CRP for assessing intersegment coordination following ankle surgeries can provide qualitative information regarding the relationship between segments in motion. The magnitude and position of the CRP peaks in the gait cycle not only provide information about joint kinematics and sensorimotor functions but also about the loading pattern in each of the foot segments. As a result, the study suggests the use of both intersegment ROM and coordination analysis in kinematic assessment of the ankle joint.

Assessing the ROM of the ankle joint following AA and TAR surgeries showed similar results as the previous studies, with both the surgical groups showing reduced mobility when compared to controls.

[28, 29] However, TAR has been shown to have a higher mobility when compared to AA patients. [10, 29, 30] Intersegment coordination between the shank and foot segments has been compared previously in anterior cruciate ligament reconstruction patients. [12] MARP results of their control group (21.2±2.7) is somewhat similar to our forefoot-shank results (20.6±3.8), while their patient group produced a significantly higher value (25.7±2.3) which is closer to the Unop side of the AA group in this study (27.8±10.2). A high MARP can be as a result of altered gait strategies, which could be related to the increased loading of the forefoot, reported in AA patients. [10]

However, ROM results show relatively normal motion for the Unop side. Postoperatively, the altered coordination strategies could be as a result of an adapted compensatory gait pattern learned during the early rehabilitation phase, due to apprehension or to prevent pain. It has also been found that an altered coordination strategy could lead to abnormal loading [19] which in the long term could be detrimental to other joints. This information is therefore, important to know when developing over through rehabilitation program. Studies have also shown the importance of gait modification strategies to reduce gait deviation following surgical corrections. This can be done using real-time movement feedback. [31, 32] Continuous gait assessment based on the intersegment coordination using wearable sensors could help improve rehabilitation by educating patients about the correct coordination strategies. This could help patients break or even prevent compensatory strategies the adopted abnormal strategies, which would have an effect, not only on improving joint kinematics, but also joint loading, [19] propulsion and, altogether, gait symmetry.

A notable strength of the study is that the wearable sensors provide freedom to test patients in open and more natural environment, instead of only a few restricted numbers of steps as commonly found in gait labs. The study also had some limitations, such as, the small subject size; however, studies assessing intersegment coordination in joint pathologies and surgical treatment have utilized similar number of participants. [12, 33]

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In conclusion, intersegment coordination, in particular, CRP mapping can provide otherwise missing information which could be beneficial in understanding and correcting a patients' compensatory gait pattern ultimately improving rehabilitation. This study has also shown that it could be used as a parameter in clinical assessment to help quantify the outcome of ankle surgeries. Future research should investigate on the reliability of intersegment coordination assessment in improving the functional outcome of ankle pathology patients.

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CURRICULUM VITAE

Swati Chopra
BPT, MSc Sports and Exercise Medicine
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Academic Qualifications

2012-2016: Doctoral student at Faculty of biology and medicine, University of Lausanne, Switzerland.

- Research carried out full-time at the motion analysis laboratory at Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne.
- Thesis title: "Development of a Gait Score for the Assessment of End-stage Ankle Osteoarthrosis and Outcome of Related Surgery".
- Supervisors: PD Dr Xavier Crevoisier.

2008-2009: MSC (Med Sc) Sports and Exercise Medicine, University of Glasgow, Scotland.

- Master's project- "Dance to fit" study assessing correlation between BMI and regular dance activity in primary school children.

2002-2006: Bachelors of Physiotherapy (BPT), Rajiv Gandhi University of Health and Science, Bangalore, India.

Courses

- ISPGR sponsored Summer School at University of Montreal on "Sensory Stimulations in Research on Posture and Gait Control and Rehabilitation"
- Excel for Data Analysis and Visualization (DAT206x) - Microsoft through edX.
- Introduction to Biomedical Imaging (BIOIMG101x) - Queensland University Australia through edX.
- Explore statistics with R (Kix-*KlexploRx*) - Karolinska Institutet through edX.
- Introduction to Statistics: Descriptive Statistics (*BerkleyX-Stat2.1x*) - UoC Berkeley through edX.
- Health in Numbers: Quantitative Methods in Clinical & Public Health Research (*HarwardX-PH207x*) - Harvard University through edX.

Work Experience

Research:

- Mayo clinic, motion analysis laboratory (2016-present) - Research related to patient recovery following total hip replacement based on physical activity levels using motion sensors. Furthermore, assisting the PT PhD staff in full biomechanical gait assessment of patients with neurologic conditions seeking surgical correction, which is used by surgeons for clinical decision making at Mayo.

- CHUV (2012-2016) - Research related to assessment of gait deviation following end-stage ankle surgeries using pressure insoles and 3-D inertial sensors. Experienced in gait assessment methods, data acquisition and understanding of abnormal gait parameters.

- University of Glasgow- Institute of Cardiovascular and Medical Sciences (2010-2012): Voluntary research under supervision of Dr Yannis Pitsiladis. Assisted in the "Identification and prevention of Dietary- and lifestyle-induced health Effects in Children and infants study" (IDEFICS), work included physical activity data analysis. http://www.ideficsstudy.eu/. Written a book chapter "Consideration in accelerometer assessment methods for children: lessons from the IDEFICS study" Chopra S, Konstabel K, Ojiambo R, Pitsiladis Y.

Clinical Training:

- East Stirlingshire, Scottish 3rd division football team, Stirling, Scotland (2011-2012): sports physiotherapist.
- Vihaan rehabilitation centre, Jabalpur, India (June 2008- August 2008): Pediatric and neuro-rehabilitation.
- Kaya life, Mumbai, India (November 2007- May 2008): Exercise specialist.
- Bombay Hospital, Mumbai, India (September 2007- October 2007): ICU care, cardiac rehabilitation.
- Jamdar Hospital, Jabalpur, India (June 2007- August 2007): Musculoskeletal rehabilitation.
- PG hospital, Jabalpur, India (Feb 2007- May 2007): Musculoskeletal rehabilitation.

Scholarships and Awards

- Certificate of Special Mention for oral poster walk presentation "Inter-Segment Coordination Using Continuous Relative Phase - An Elaborative Perspective to Study Kinematics in Ankle Joint" at the 17th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2016, Geneva, Switzerland
- Awarded Distinction in poster presentation "Bilateral Gait Mechanics in End Stage Ankle Arthrosis" at the 16th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference, May 2015, Prague, Czech Republic.
- Awarded Distinction in poster presentation "Gait Variability in Ankle Osteoarthritis, Ankle Arthodesis and Total ankle Replacement" at the 16th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference, May 2015, Prague, Czech Republic.
- Awarded a 4 year PhD research grant of ~190,000 CHF from the Département de l'Appareil Locomoteur (DAL) at the Centre hospitalier universitaire vaudois (CHUV)
- Awarded a scholarship towards fee for MSc in exercise and sports medicine from the University of Glasgow.

Research Interests

- Clinical biomechanics
- Movement disorders

- Movement anaylsis
- Wearable activity monitoring system
- Osteoarthritis
- Orthopaedic surgeries
- Sports rehabilitation

Software Skills

Familiar with: MS Excel, Power Point, MS Word, STATA, R and MATLAB

Membership of societies

- International Society of Biomechanics (ISB)
- International Society of Posture and Gait Research (ISPGR)
- Health Professional Council (HPC), UK
- Indian Association Of Physiotherapist

Bibliography

Journal Articles

[1] **Chopra S**, Crevoisier X. Bilateral Gait Mechanics in End-stage Ankle Osteoarthrosis. (submitted).

[2] **Chopra S**, Favre J, Crevoisier X. Qualitative Analysis of Foot Intersegment Coordination in the Sagittal Plane for Ankle Osteoarthrosis Surgeries. (revision submitted).

[3] **Chopra S**, Pichonnaz MJ, Crevoisier X. Gait Mechanics after Tibiotalocalcaneal Arthrodesis *vs* Tibiotalar Arthrodesis. (submitted).

[4] **Chopra S**, Moerenhout K, Crevoisier X. Subjective vs Objective Assessment in Early Clinical Outcome of Modified Lapidus Procedure for Hallux Valgus Deformity. Clinical Biomechanics (in press) DOI: http://dx.doi.org/10.1016/j.clinbiomech.2015.11.012.

[5] **Chopra S**, Rouhani H, Moerenhout K, Favre J, Aminian K, Crevoisier X. Outcome of Ankle Arthrodesis and Total Ankle Replacement for Ankle Arthrosis in Terms of Gait Variability. Journal of Biomedical Engineering and Informatics DOI: 10.5430/jbei.v2n1p31.

[6] **Chopra S**, Moerenhout K, Crevoisier X. Characterization of gait in female patients with moderate to severe hallux valgus deformity, Clin Biomech (Bristol, Avon). 2015 Mar 28. pii: S0268-0033(15)00097-2. doi: 10.1016/j.clinbiomech.2015.03.021.

[7] **Chopra S**, Rouhani H, Assal M, Aminian K, Crevoisier X. Outcome of unilateral ankle arthrodesis and total ankle replacement in terms of bilateral gait mechanics. J Orthop Res. 2014 Mar; 32(3):377-84. doi: 10.1002/jor.22520.

[8] Burn A, Buerer Y, **Chopra S**, Winkler M, Crevoisier X. Critical evaluation of outcome scales assessment of lateral ankle ligament reconstruction. Foot Ankle Int. 2013 Jul; 34(7):995-1005. doi: 10.1177/1071100713481669.

[9] Buerer Y, Winkler M, Burn A, **Chopra S**, Crevoisier X. Evaluation of a modified Broström-Gould procedure for treatment of chronic lateral ankle instability: A retrospective study with critical analysis of outcome scoring. Foot Ankle Surg. 2013 Mar; 19(1):36-41. doi: 10.1016/j.fas.2012.10.005.

Conferences

Free Papers

[1] **Chopra S**, Baalbaki R, Pichonnaz MJ, Crevoisier X. Gait Mechanics After Tibiotalocalcaneal Arthrodesis *vs* Tibiotalar Arthrodesis. Intl. Symposium in Honour of Dr An, Mayo Clinic, Rochester MN, Aug 2015.

[2] **Chopra S**, Baalbaki R, Pichonnaz M J, Favre J, Crevoisier X. Biomechanical Comparison of Tibiotalocalcaneal and Tibiotalar Fusion. International Society of Biomechanics 2015, Glasgow.

[3] **Chopra S**, Moerenhout K, Crevoisier X. Characterization of gait in female patients with moderate to severe hallux valgus deformity. Swiss Orthopaedic Society 2015, Basel.

[4] **Chopra S**, Favre J, Crevoisier X. Analysis of foot segment coordination along with joint angulations- a more elaborative perspective to study kinematics in ankle joint. Swiss Orthopaedic Society 2015, Basel.

[5] **Chopra S**, Baalbaki R, Pichonnaz M J, Favre J, Crevoisier X. Tibiotalocalcaneal vs tibiotalar fusion: a biomechanical comparison. Swiss Orthopaedic Society 2015, Basel.

[6] **Chopra S**, Baalbaki R, Pichonnaz M J, Favre J, Crevoisier X. Gait Mechanics After Tibiotalocalcaneal Arthrodesis In Comparison With Tibiotalar Arthrodesis: A Biomechanical Study. 16th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2015, Prague. **(Nominated for free paper award)**

[7] **Chopra S**, Rouhani H, Moerenhout K, Favre J, Aminian K, Crevoisier X. Outcome of Ankle Arthrodesis and Total Ankle Replacement for Ankle Osteoarthrosis in Terms of Gait Variability. Swiss Orthopaedic Society 2014, St. Gallen.

[8] **Chopra S**, Rouhani H, Assal M, Aminian K, Crevoisier X. Analysis of the effect of Ankle Arthodesis and Total Ankle Replacement on Plantar Pressure and Gait Symmetry. 14th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2013, Istanbul.

[9] Rouhani H, Favre J, Aminian K, **Chopra S**, Crevoisier X. An Ambulatory System for Kinematic and Kinetic Analysis of Gait. 24th Congress of the International Society of Biomechanics 2013, Natal, Brazil.

Posters

[1] **Chopra S**, Favre J, Crevoisier X. Inter-Segment Coordination Using Continuous Relative Phase - An Elaborative Perspective to Study Kinematics in Ankle Joint. 17th European

Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2016, Geneva, Switzerland.**(Certificate of Special Mention)**

[2] **Chopra S**, Crevoisier X. Biomechanical Principal component Models for the Ankle: A Comparison of Normal, Osteoarthrosis and Postoperative Gait Patterns. 17th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2016, Geneva, Switzerland.

[3] **Chopra S**, Crevoisier X. Bilateral Gait Mechanics in End Stage Ankle Arthrosis. 16th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2015, Prague. **(Distinction award)**

[4] **Chopra S**, Rouhani H, Moerenhout K, Favre J, Aminian K, Crevoisier X. Gait Variability in Ankle Osteoarthritis, Ankle Arthodesis and Total ankle Replacement. 16th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2015, Prague. **(Distinction award)**

[5] **Chopra S**, Moerenhout K, Crevoisier X. Subjective vs Objective Assessment in Early Clinical Outcome of Modified Lapidus Procedure for Moderate to Severe Hallux Valgus Deformity. 13th International Symposium on 3D Analysis of Human Movement 2014, Lausanne.

[6] **Chopra S**, Moerenhout K, Crevoisier X. Determination of Clinically Beneficial Gait Parameters of Severe Hallux Valgus Deformity. 15th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2014, London.

[7] Burn A, Buerer Y, **Chopra S**, Winkler M, Crevoisier X. Critical evaluation of outcome scales assessment of lateral ankle ligament reconstruction. 14th European Federation of National Associations of Orthopaedics and Traumatology (EFORT) Conference 2013, Istanbul.