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Authors: Chopra S, Favre J, Crevoisier X

Journal: Journal of orthopaedic research : official publication of the Orthopaedic Research Society

Year: 2017 Jun

Issue: 35

Volume: 6

Pages: 1304-1310

DOI: 10.1002/jor.23379

Research Article

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

Running title: Intersegment Coordination following Ankle Surgeries

Swati Chopra[1*], Julien Favre[2], Xavier Crevoisier[3]

*Swati Chopra, PT MSc (corresponding author)
[1] Department of Orthopaedic Surgery and Traumatology, Centre Hospitalier Universitaire Vaudois (CHUV) and University of Lausanne (UNIL), Pierre-Decker 4, CH-1011 Lausanne, Switzerland. schopra.research@gmail.com
Julien Favre, PhD
[2] Swiss Biomotion Lab, Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne, Switzerland. julien.favre@chuv.ch
Xavier Crevoisier, MD, PD
[3]Department of Orthopaedic Surgery and Traumatology, Lausanne, Centre Hospitalier Universitaire Vaudois (CHUV) and University of Lausanne (UNIL), Switzerland. xavier.crevoisier@chuv.ch, contact: +41 (0) 21 314 97 27 TEL

Author's contributions: All authors were fully involved in the study, including the preparation of study design, data collection, statistical analysis/ interpretation and preparation of the manuscript.

†This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: [10.1002/jor.23379]

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Abstract

Today, ankle joint kinematic assessment gives important information regarding the intersegment range of motion. It does not, however, provide information regarding coordination between the segments. 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 overlooked by the 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

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 kinematics, 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 model was 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 model 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]

Looking at 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. For example, ankle arthrodesis (AA) the most commonly used surgical treatment for end-stage ankle osteoarthrosis, where the degenerated tibiotalar/ ankle joint is fused at a neutral position, such that the joint has zero motion. The second commonly seen surgical treatment is total ankle replacement (TAR) where the diseased ankle joint is replaced by an artificial joint such that the new joint mimics the original joint biomechanically, in terms of freedom of motion. Knowing this, 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.[16] 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.

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. Difference in the functional status of the patients in the two surgical groups were not significant based on the foot and ankle ability measure score (FAAM) with average scores of 70 (16.8) and 80 (17.1) for AA and TAR, respectively. 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 and 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 participant for optimal placement of sensors. Following the preparation of each participant, functional calibration was performed,[17, 16] after which the participants walked 50 m along the hospital corridor twice at their natural pace. Average walking speeds were reported to be 1.26 (0.19) m/s in controls, 0.94 (0.21) m/s for ankle arthrodesis (AA) patients and 1.09 (0.16) m/s for total ankle replacement (TAR) patients. For the surgical group, both operative (Op) and unoperated (Unop) sides were tested. Note that the test retest reliability of the utilized gait assessment method and protocol have 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 into7 subphases[19] including:

Loading response: represents the initiation of the gait cycle from the time of initial heel strike to the complete contact of the foot with the ground. It constitutes the first 0-10% gait cycle time (GCT).

Mid-stance: represents the time when the foot is completely in contact with the ground as well as being fully loaded, i.e., the single support duration of the gait cycle. It constitutes 10-30% of the GCT.

Terminal-stance: represents the duration when the heel is off the ground and the body weight is divided over the forefoot region. It constitutes 30-50% of the GCT.

Pre-swing: represents the toe-off duration when the foot is about to leave the ground, i.e., leaving the stance phase and entering the swing phase. It constitutes 50-62% of the GCT.

Initial-swing: represents start of the swing phase, when the foot leaves the ground. It constitutes 62-75% of the GCT.

Mid-swing: represents the duration when the foot is midway through the swing phase, i.e. at the furthest away from the ground. It constitutes 75-85% of the GCT.

Terminal-swing: represents the end of the gait cycle, when the heel touches the ground for initial contact. It constitutes 85-100% of the GCT.

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.

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), CRP curve and MARP were calculated for each gait cycle for the three intersegments. 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] Comparisons between groups were performed using the Wilcoxon rank sum test, however, for intra group bilateral comparisons, the Wilcoxon signed rank test was used ($p<0.05$).

Results

Intersegment coordination

Evaluation of the CRP curves found various peak patterns in each of the three intersegments among the study groups (Figure 2). Forefoot-hindfoot intersegment, when compared to the controls showed significantly low peaks during the mid-stance and initial swing phase in AA Op side while AA Unop side showed significantly large positive peak at the terminal stance and low peak at the initial swing phase compared to the controls ($p<0.05$). 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 stance phase. Such an over activity at the forefoot may be detrimental to the joint long-term. In contrast, TAR patients reported no significant difference in their intersegment coordination peak pattern, when compared to the controls. Op to Unop side comparison showed significant difference in the peaks at the loading, mid and terminal stance phases for AA patients, representing a bilateral asymmetry during the stance phase, but again, no difference was reported for TAR patients. Comparing the Op side of AA and TAR groups reported significantly low peak at mid stance and initial swing phases in AA 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 (Table 1), this is likely due to the increased rotation at the forefoot segment.

Looking at the hindfoot-shank intersegment, in contrast to the controls little to no peak was reported during the initial swing phase for both Op and Unop sides of AA patients. 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. 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 in AA group reported significant difference at initial swing with increased rotation on the Unop side. While in TAR group, similar comparison reported significant difference at terminal stance with increased rotation on the Unop side, furthermore, during initial swing Op and Unop sides reported different segments dominating the motion, hindfoot for Op side and shank on the Unop side, representing significantly different peaks and direction of rotation. No difference was reported between the Op sides of the two surgical groups. 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, Op side in both surgical groups reported 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 initial swing on the Op and Unop side of both TAR and AA groups, while the Unop side of AA also reported significantly large peaks at mid and terminal stance phases compared to the control. For the Op to Unop side comparison, AA patients showed significantly different peaks during the mid-stance, terminal stance, pre swing and mid swing phases, likely due to the over activity of the forefoot segment on the Unop side. On the other hand, TAR patients also reported significantly different peaks at the terminal stance and initial swing phases between the two sides. Comparing the Op sides of both surgical groups, TAR patients showed a significantly large peak during the initial swing 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 surgical groups reported a low MARP, representing an overall reduction in mobility.

Lastly, the CMC for forefoot-hindfoot and forefoot-shank CRP curves was found to be strong, 0.95 and 0.98, respectively, indicating comparable inter-joint coordination patterns between each group. However, a moderate CMC value of 0.8 for hindfoot-shank intersegment could be the result of the altered coordination pattern on the Op side of both AA and TAR patients, during the swing phase, which resulted in a lesser predictable fit.

Intersegment displacement

The mean joint angular displacement results, based on inter-segment rotations, are given in (Table 2). In comparison to the controls all three intersegment reported significantly low motion on the Op side of AA patients while for Op side of TAR significantly low motion was reported at hindfoot-shank and forefoot-shank intersegments. Op to Unop side comparison in AA group reported significantly reduced motion at all three intersegments on the Op side in comparison to their Unop side. Similar comparison for TAR group reported significantly reduced motion at the forefoot-shank intersegment on the Op side in comparison to their Unop side. Transition between dorsi and plantar flexion motion at different phases of the gait, during 100 % of the gait cycle is given in (Figure 3). 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 surgical groups showed significant differences in forefoot-hindfoot and forefoot-shank intersegments.

Discussion

This study aimed to introduce intersegment coordination when assessing the kinematics of the ankle joint by utilizing CRP as it has generally not been studied for foot and ankle joint surgeries. The purpose of the study was not to compare the outcome of the two surgeries but to see if CRP method for intersegment coordination assessment adds information which could be of any benefit for clinicians to improve outcome in patients with different ankle surgeries. The study provided baseline bilateral intersegment coordination patterns for the controls and two common ankle surgeries: AA and TAR. 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 for both Op and Unop sides. 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 on the Op side when compared to controls.[28, 29] However, TAR has been shown to have a higher mobility when compared to AA patients.[10, 29, 30]

It is evident in our results that the amount of intersegment rotation does not represent coordination between the segments. For instance, in the present study, the Unop side of AA patients reported ROM for all three intersegments – similar to the controls. However, the intersegment coordination strategy for each intersegment is seen to differ significantly from the controls. This alteration in coordination could be due to the compensatory gait pattern adapted by the patient after the surgery as a result of fusing the ankle. It is therefore advised to study bilateral intersegment coordination patterns to understand the effect of a surgery on both Op and Unop sides, as continuous altered gait mechanics may lead to abnormal loading[19] further developing joint problems in long-term. Furthermore, radiographic outcome of long-term AA patients have reported development of moderate to severe degenerative changes in the surrounding joints of the foot on the Op side, while the contralateral Unop side is reported to be susceptible for development of arthritis in midfoot and hindfoot regions [31]. On the other hand, TAR is known to maintain the normal mechanics of the ankle joint, unlike the AA surgery, but practically it does not resume complete ankle function and the replaced joint is shown to have some restriction in joint ROM and altered coordination pattern between the segments. This information regarding the adapted coordination strategies is notably missing in the literature for post ankle surgeries.

It is of note that, the study does not suggest that post operatively patients should walk similar to the controls, when it is clearly not possible in surgery like AA were the ankle joint is fused. However, comparison is made between the intersegment patterns of controls with the surgical groups to understand the alterations in intersegment coordination after individual surgery. This information is important to develop a base line expectation for the patients and find if there is a scope to improve some of the coordination strategies adapted by the patient, bilaterally, to prevent problems in long run due to the persistent limp [31].

Furthermore, studies have also shown the importance of gait modification strategies to reduce gait deviation, as much as possible, following surgical corrections. This can be done using real-time movement feedback.[32, 33] Continuous gait assessment based on the intersegment coordination using wearable sensors could help improve rehabilitation by helping patients learn the most efficient gait pattern which could benefit not just the operated but the surrounding joints. This could help patients break unwanted and potentially harmful compensatory strategies which would further help improve joint kinematics along with the bilateral joint loading. [19] The objective of post-operative rehabilitation is to optimize the walking function as much as possible and prevent further joint problems in long-term. Intersegment coordination could play an important role in this by helping clinicians understand the alterations in gait mechanics and to find ways to minimize these alterations to a desired level.

Comparing the CRP outcome with the existing studies, the intersegment coordination between the shank and forefoot segments has been compared previously in anterior cruciate ligament reconstruction patients.[12] MARP results of their control group (21.2±2.7) are 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 a result of altered gait strategies, which could be related to the increased loading of the forefoot, reported in AA patients.[10]

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's primary limitation is the small subject size. However, studies assessing intersegment coordination in joint pathologies and surgical treatment have utilized similar number of participants.[12, 34] Another limitation of the study is the difference in the walking speed of the patients in different study groups, as slow walking speed is shown to have an effect on the ROM of joints [35] this may have an effect on the ISC pattern.

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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Legends

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

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

Figure 3: Graph presenting dorsi and plantar flexion movement in the sagittal plane over 100% of the gait cycle; black line represents controls, bold line represents operated side and dot line represent unoperated side. ★represents significant difference to the controls.

Table 1: Mean Absolute Relative Phase, mean (SD)

Table 2: Angular displacement, in the sagittal plane, for three intersegments, means (SD)

Tables

Table 1: Mean Absolute Relative Phase, mean (SD)

Intersegments CRP	CON	TAR Op	TAR Unop	AA Op	AA Unop	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 ($p<0.05$)

Table 2: Angular displacement, in the sagittal plane, for three intersegments, means (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 ($p<0.05$)

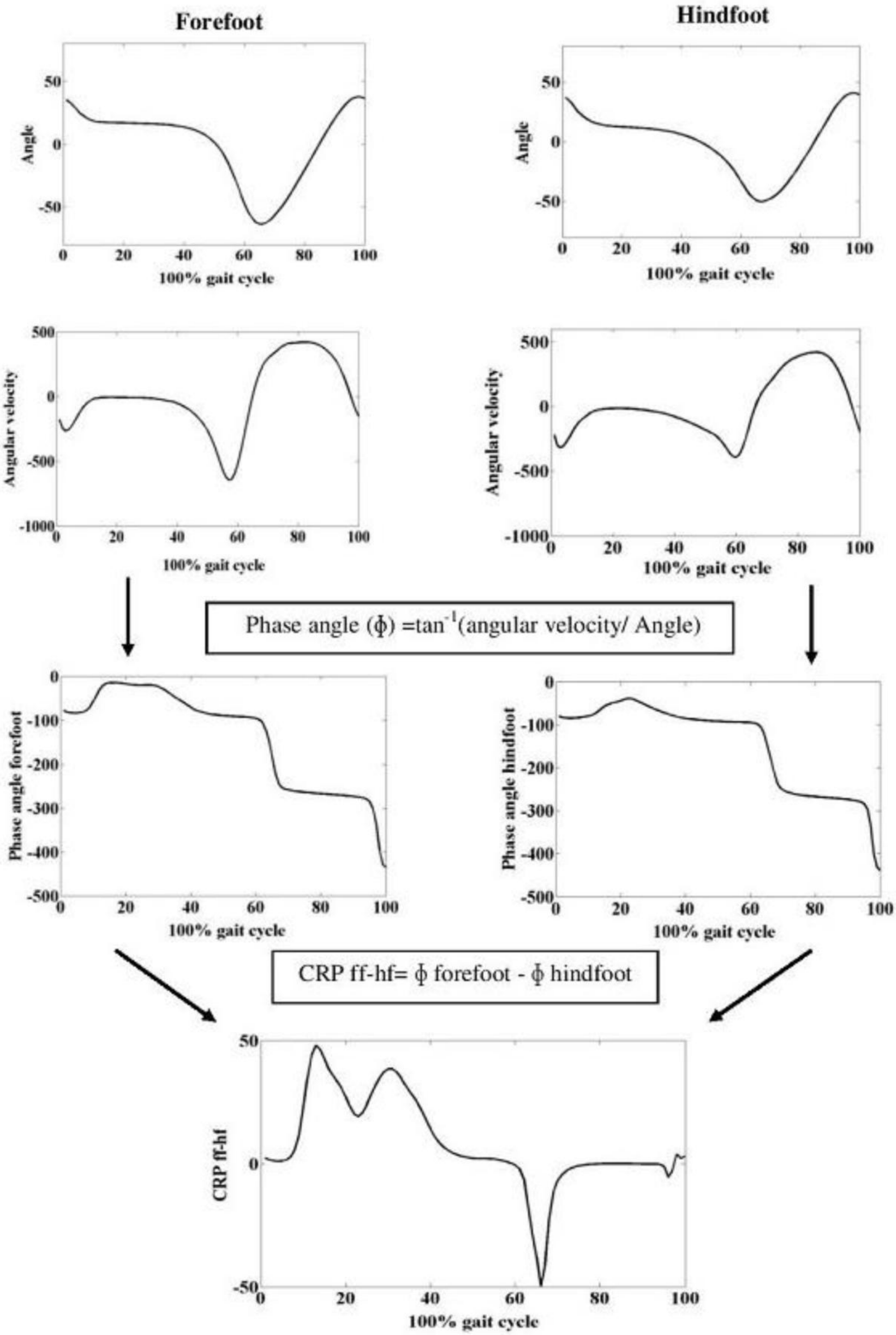
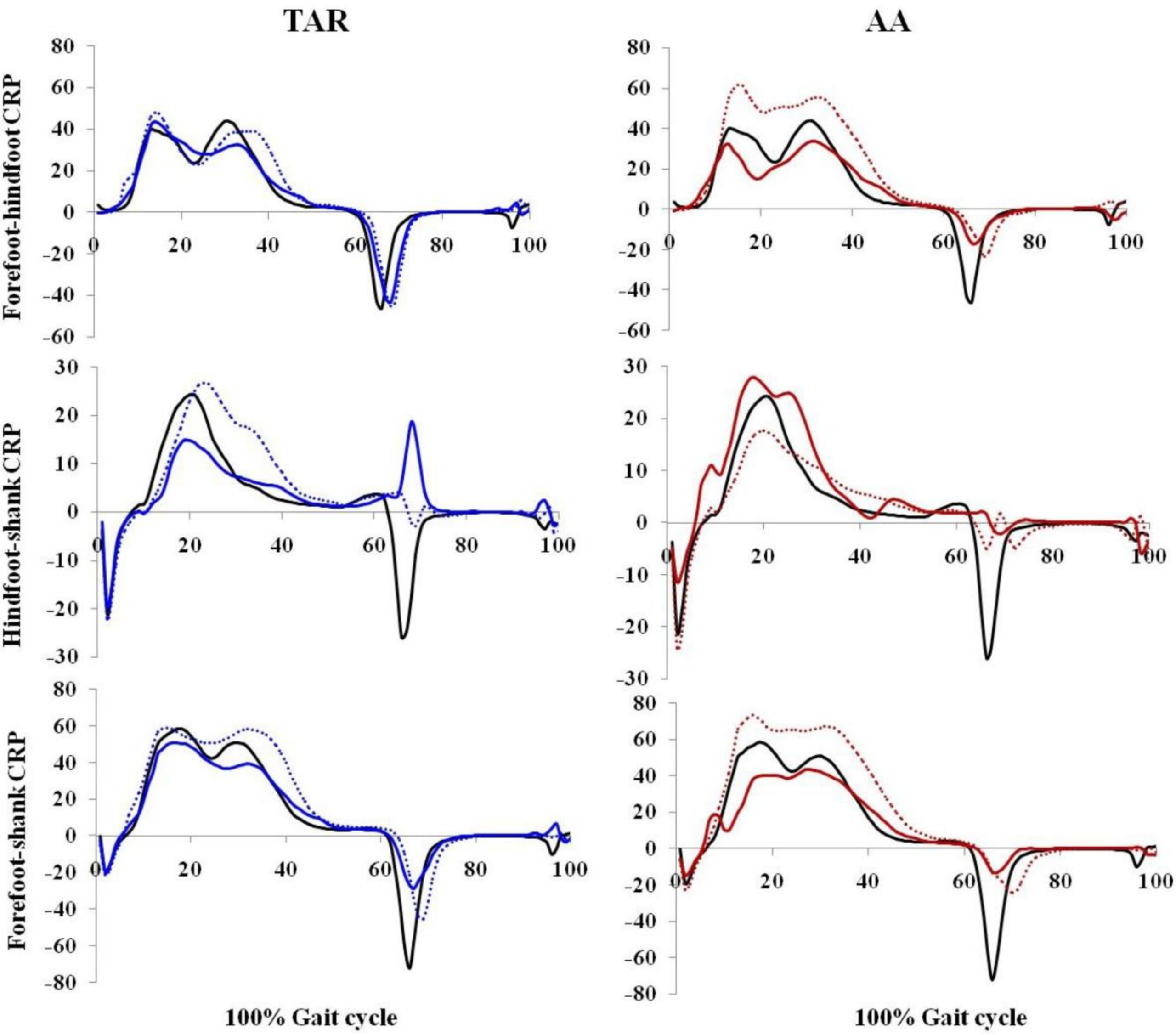

Forefoot
Hindfoot
Angle
100% gait cycle
Angular velocity
Phase angle (ϕ) =tan-1(angular velocity/ Angle)
Phase angle forefoot
Phase angle hindfoot
CRP ff-hf= ϕ forefoot - ϕ hindfoot
CRP ff-hf

Figure 1



TAR
AA
Forefoot-hindfoot CRP
Hindfoot-shank CRP
Forefoot-shank CRP
100% Gait cycle
100% Gait cycle

Figure 2

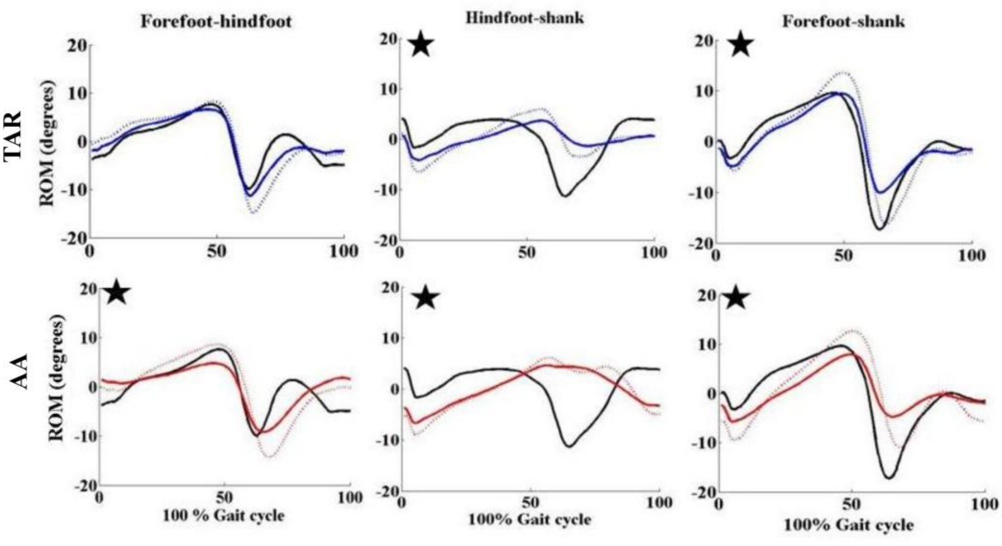

Forefoot-hindfoot
Hindfoot-shank
Forefoot-shank
TAR
AA
ROM (degrees)
20
10
0
-10
-20
0
50
100
100 % Gait cycle
100% Gait cycle

Figure 3