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Lower limb muscle activity during first and second tennis serves: a comparison of three surface electromyography normalisation methods

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ABSTRACT

We assessed lower limb muscle activity during the execution of first and second tennis serves, exploring whether the extent of these differences is influenced by the chosen method for normalising surface electromyography (EMG) data. Ten male competitive tennis players first completed three rounds of maximal isometric voluntary contractions (MVC) of knee extensors and plantar flexors for the left (front) and right (back) leg separately, and three squat jumps. Afterward, they executed ten first and ten-second serves. Surface EMG activity of four lower limb muscles (*vastus lateralis*, *rectus femoris*, *gastrocnemius lateralis*, and *soleus* muscles) on each leg was recorded and normalised in three different ways: to MVC; to peak/maximal activity measured during squat jump; and to the actual serve. For the *rectus femoris* and *soleus* muscles of the left leg, and the *gastrocnemius lateralis* and *soleus* muscles of the right leg, EMG amplitude differed significantly between normalisation techniques ($P \leq 0.012$). All muscles showed greater activity during the first serve, although this difference was only statistically significant for the right *vastus lateralis* muscle ($P = 0.014$). In conclusion, the EMG normalisation method selected may offer similar information when comparing first and second serve, at least for leg muscles studied here.

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Introduction

Modern-day tennis players are capable of serving the ball at velocities exceeding 200 km/h. The serve, being the only closed skill in tennis, grants the server the advantage of setting the tone of the point right from the beginning. However, executing a successful serve requires coordination between lower and upper body segments to achieve an

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optimal racket position, height, and velocity at the moment of ball impact (Elliott, 1986). Numerous serve kinematic analyses have carefully described the sequencing of the trunk, upper arm, forearm, and hand segments (Bahamonde, 2000; Elliott et al., 1995). Comparatively, fewer studies have specifically examined lower limb drive (Girard et al., 2005; Van Gheluwe & Hebbelinck, 1986). In investigating the leg actions that distinguish the serve of players with different performance calibre, Girard et al. (2005) found players of higher performance levels to generate higher amounts of vertical ground reaction forces (GRF) than their less skilled counterparts.

Surface electromyography (EMG) is often used to assess intermuscular coordination (Hug, 2011) and/or timing of muscle activation-relaxation (Hodges & Bui, 1996) as well as changes in neural drive following an intervention (Piirainen et al., 2014). Several factors can affect EMG signal amplitude (i.e., skin thickness, electrode characteristics, and distance from the skin's surface to the active motor units) causing non-physiological between-participant variability (Farina et al., 2004). Consequently, normalisation of EMG signals to a reference value is required to compare data between different muscles, tasks, and/or individuals (Lehman & Mcgill, 1999). Normalisation rescales the raw EMG amplitudes from millivolts into a percentage of this reference value and is usually achieved by dividing the EMG signals during a task by a reference EMG value obtained from the same muscle (Burden & Bartlett, 1999). Despite several decades of research (Eberhart et al., 1954), there is still no consensus as to which methods used to normalise EMG signals produce maximal activation levels in all individuals in any given muscle (Burden, 2010).

The most common EMG normalisation procedure is probably to use the reference value derived from the same muscle during a maximal isometric voluntary contraction (MVC) (Burden & Bartlett, 1999). However, when normalising EMG data to a multi-joint high-velocity dynamic task such as serving in tennis, many differences in the actions of the muscles involved make the relevance of isometric contractions questionable (Ball & Scurr, 2013). The EMG signal from a relatively unfamiliar movement pattern (i.e., isolated muscle actions) may not represent the maximum activation capacity of the studied muscle group at lengths other than those at which the MVC was performed or under non-isometric conditions (Mirka, 1991). Additionally, testing separately the muscles in tasks and positions that considerably differ from the tennis serve is particularly time-demanding (Hsu et al., 2006), especially when multiple muscles (i.e., each requiring several MVC trials) are investigated.

In recent years, dynamic normalisation tasks, such as squat jumps (SJ) and 20-m sprints (Ball & Scurr, 2011; Le Mansec et al., 2018), have been increasingly used for leg muscles. Although they have limitations (i.e., muscle movement relative to the skin, noise sensitivity), these normalisation methods using fast muscle actions generally provide high activation levels and *good* EMG data reliability (Ball & Scurr, 2011). This procedure, which requires less time to complete compared to MVC is likely more practical, with the additional possibility to assess maximal activation capacity of all leg muscles from a single performance test (Ball & Scurr, 2013). An alternative dynamic normalisation method is to quantify peak or mean activation levels obtained during the task under investigation (Ghazwan et al., 2017). Here, the EMG data is normalised to the peak or mean activity obtained during the activity in each muscle for each individual separately. For instance, Gagnat et al. (2020) reported EMG signals from five leg muscles during walking as a percentage of the peak muscle activity that occurred during the gait cycle. Overall, dynamic normalisation procedures are more time-efficient and allow for the assessment of maximal activation capacity of multiple leg muscles in a single performance test.

It is common in gait (Burden et al., 2013) and cycling (Rouffet & Hautier, 2008) studies to use EMG normalisation methods with leg actions similar to the actual task. Conversely, tennis studies have in general not adopted similar procedures for expressing muscle activity levels in the lower extremities (Fenter et al., 2017; Girard et al., 2005). To our knowledge, a comparison of different surface EMG normalisation procedures (i.e., as reviewed above) for lower extremities while executing first and second serves has never been done before.

This study aimed to determine which of three normalisation techniques (i.e., MVC, SJ, and actual serve) would produce the greatest reference EMG amplitude, and verify whether muscle activity of lower limbs differs between first and second serves. We hypothesised that leg muscles on both sides would be more strongly activated during the fastest serve and that ballistic isometric tasks would produce greater EMG values.

Materials and methods

Participants

Ten right-handed male competitive players (mean±SD: age 26.1 ± 4.7 years; height 181.5 ± 6.8 cm; body mass 76.3 ± 7.6 kg) competing at regional to national levels (international tennis ranking ranging from 2 to 4) participated in the study. Participants were classified as 'Tier 2: Trained/Developmental' according to the participant classification framework proposed by McKay et al. (2022). They were eligible if they had no history of injury to the lower extremities within the past year. The experiment was approved by the local Ethics committee and conformed to the current *Declaration of Helsinki* guidelines.

Experimental set-up

All experiments were conducted on an indoor tennis court. Participants first performed a warm-up consisting of ~5 min jogging, followed by ~5 min of athletic drills (i.e., heel flicks, high knee runs, coordination skips, hopping, and progressive accelerations). Subsequently, surface EMG electrodes were affixed to the skin (see below). Two maximal tests were then performed, which included the measurement of MVC for the knee extensors and plantar flexors in a randomised order followed by the assessment of SJ after 5 min of rest, to determine a maximal value of the muscle activity for each recorded muscle (i.e., see 'normalization procedure' *below*). After a standardised tennis warm-up lasting ~15 min including baseline play and practice serves, participants were requested to complete first and second serves in a randomised order (i.e., see 'tennis serves' *below*). During each trial, EMG signals of four muscles on each leg (a total of eight muscles studied) were recorded.

Maximal voluntary isometric contractions

Participants performed brief (~5 s) MVC of the knee extensors and plantar flexors for both the left (front) and right (back) leg. This was preceded by a brief warm-up consisting of six submaximal contractions of ~2–3 s in duration, interspaced with ~10–20 s of recovery, at progressive intensity. For knee extensors, participants were seated upright on a custom-built adjustable chair with the hips and knees flexed at 90°. Restraining straps placed across the chest and hips secured the participants in the chair to prevent extraneous movement, while the dynamometer (Captels, St Mathieu de Treviers, France) was attached 3–5 cm above the tip of the lateral malleoli. For plantar flexors, a dynamometric pedal (Captels, St Mathieu de Treviers, France) was used with the participants seated upright with their hips, knee, and ankle flexed at 90°, 100°, and 90°, respectively. The foot of the leg performing the MVC was secured to the dynamometric pedal with two restraining straps. Force traces were recorded at a sampling frequency of 1000 Hz. For both knee extensors and plantar flexors, participants were asked to perform three maximal trials while instructed to contract '*as hard as possible*' sustaining the contraction for 3–5 s, each separated by 1 min of rest to avoid fatigue effects. For the final analysis, the best of three trials was recorded for knee extensors and plantar flexors MVC of each leg.

Squat jumps

After 3–5 warm-up trials where participants were instructed with appropriate technique (i.e., hands kept on the hips to eliminate any influence of arm swing), three maximal SJs separated by 1 min rest were executed. Each trial started from a static semi-squatting position (~90° of flexion) maintained for ~1 s and without any preliminary movement and was performed with the trunk as straight as possible. This normalisation method was chosen as it uses a familiar movement (i.e., often performed as part of the regular testing routines of tested players) and involves explosive leg muscle actions (Ball & Scurr, 2013) as for tennis serves. Maximal SJs were previously used to normalise surface EMG recordings of both the knee extensors and plantar flexors during seven common table tennis strokes (Le Mansec et al., 2018). The best of three SJ trials was considered for subsequent analysis.

Tennis serves

All first and second serves were completed from the 'deuce' or right service court. Specifically, participants were requested to hit their serves to a 1 × 1 m target area bordering the 'T' of the right service box at a match pace. Ten 'successful' trials were collected, as judged by a professional coach. The requirement for these trials was that first serves be executed with minimum spin on the ball, while second serves were characterised by a combination of topspin and sidespin (Girard et al., 2010). All participants were right-handed and used their racquet (small variations in mass, string, tension, and flexibility) in an endeavour to ensure that they felt comfortable performing each serve. In all trials, participants adopted a ready position with the two feet (front: left leg; back: right leg) located on a force platform (surface area: 100 × 80 × 7 cm) until the takeoff instant and were instructed to hit the ball like in an official competition. The force platform, installed on the right side of the baseline, was used to monitor peak vertical forces at a sampling frequency of 500 Hz (MP 100A-CE, Biopac, Santa Barbara, CA). Maximum ball velocity was recorded using a radar gun (Stalker ATS, MN) fixed on a 2.5-m high tripod, 2 m behind the players.

Electromyographic recordings and normalization procedures

Muscle activity was recorded by means of surface electrodes (Bagnoli 8-EMG system, Delsys, USA) from eight muscles including the *vastus lateralis* (VL), *rectus femoris* (RF), *gastrocnemius lateralis* (GL) and *soleus* (SOL) of each leg. The electrodes were located and placed according to SENIAM's recommendations (Hermens et al., 2000). Before fixing electrodes, the skin was shaved, lightly abraded, and cleaned with alcohol to reduce impedance. Electrodes and cables were all secured to the skin with an elastic cohesive bandage to reduce movement artefacts. EMG was pre-amplified close to the electrodes (×1,000), band-pass filtered (high-pass 20, low-pass 450 Hz), and full-wave rectified. To obtain the EMG envelope, the raw data was processed by applying full-wave rectification and a fourth-order Butterworth low-pass filter with a cut-off frequency of 5 Hz (Hansen et al., 2017).

The highest value of the EMG envelope during the two maximal tests (MVC and SJ) was retained and was considered as the reference; *i.e.*, the maximal level of activity, regardless of when the moment of the EMG peak occurred (Le Mansec et al., 2018). The same procedure was used to determine peak EMG amplitude during the first and second serves. Subsequently, EMG amplitude was averaged for each muscle and each serve type over the ten successful trials. Finally, the magnitude of EMG signals was compared after normalising them using peak/maximal values from three methods: i) MVC, ii) SJ, and iii) actual serve (SERVE).

Statistical analysis

Data were analysed using JASP Team 2023 (Version 0.17.2). The Kruskal-Wallis test was chosen due to the small sample size, in addition to the Shapiro-Wilk test indicating a significant departure from normality in the distribution of the variables ($P < 0.01$), and Levene's test demonstrating equality of variances ($P > 0.01$). Dunn's Tests with Bonferroni adjusted P-values were conducted when a significant main effect was observed. For the follow-up tests, Cohen's effect sizes d_z are reported, with small, moderate, and large effects considered for $d_z \geq 0.2$, $d_z \geq 0.5$, and $d_z \geq 0.8$, respectively. Paired samples t-tests were performed on peak vertical force and maximum ball velocity. Statistical significance was accepted at $P < 0.05$.

Results

For the RF and SOL muscles of the left leg, and the GL and SOL muscles of the right leg, EMG amplitude differed significantly between normalisation techniques ($P \leq 0.012$) (Figure 1 and Table 1).

For the left leg, EMG activity of RF and SOL was lower for SERVE compared to both MVC ($P = 0.007$ and $P < 0.001$, respectively) and SJ ($P = 0.006$ and $P < 0.001$, respectively).

For the right leg, EMG activity of GL was lower for both SJ ($P = 0.009$) and SERVE ($P < 0.001$) compared to MVC. Additionally, EMG activity of the right SOL exhibited lower values during SERVE compared to SJ ($P = 0.001$).

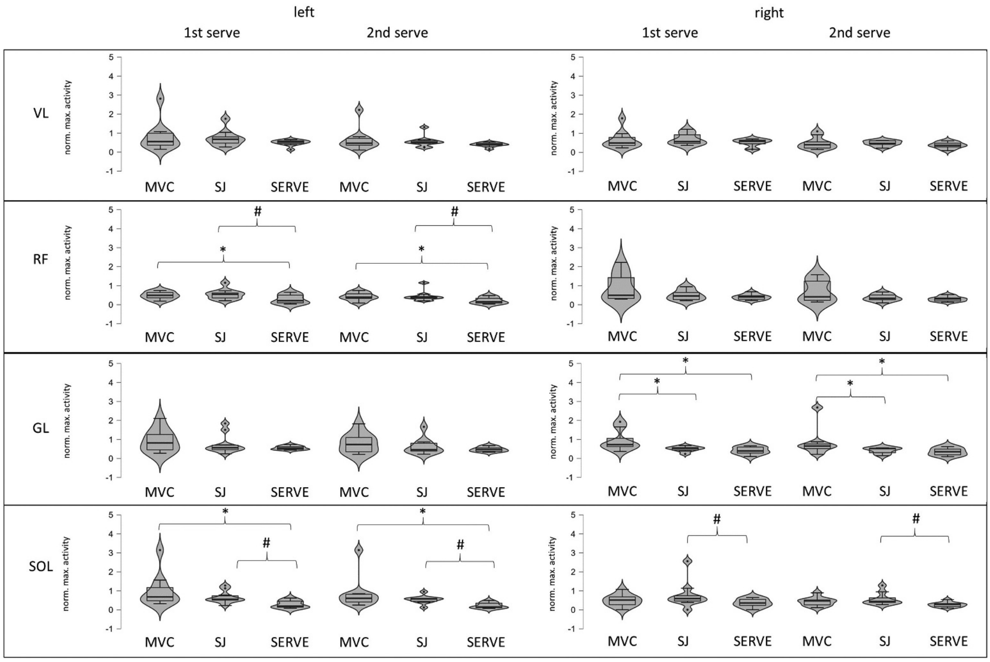

Figure 1. Violin plots visualising the three normalisation methods for surface electromyographic activity of eight muscles during the first (1st serve) and second (2nd serve) tennis serves. Surface electromyography activity (EMG) for four muscles (vastus lateralis [VL], rectus femoris [RF], gastrocnemius lateralis [GL] and soleus [SOL]) of the left (top panels) and right (bottom panels) leg was normalised to maximal activity measured during isometric maximal voluntary contractions (MVC) and squat jump (SJ) as well as peak values obtained during actual tennis serves (SERVE). Kruskal-Wallis test for normalisation method and service type are stated along with partial-eta squared (η^2) and [Cohen's d]. * significantly different from MVC ($P < 0.05$); # significantly different from SJ ($P < 0.05$).

The right VL muscle exhibited a main effect of serve type ($P = 0.014$), with higher EMG levels for first than second serves (Figure 1 and Table 1).

Maximum ball velocity was faster for first than second serves (156 ± 11 *vs.* 125 ± 17 km/h; $P < 0.001$, $d = 2.12$; Figure 2(a)). Peak vertical forces did not differ between first and second serves (1.7 ± 0.3 *vs.* 1.7 ± 0.2 body weight; $P = 0.498$, $d = 0.23$; Figure 2(b)).

Discussion and implications

Comparison of normalization methods

Our main finding was that different EMG normalisation procedures lead to significant differences in the relative EMG amplitude developed during the serve (i.e., RF and SOL muscles of the left leg, and the GL and SOL muscles of the right leg). To our knowledge, no previous EMG study has addressed the issue of the best-suited normalisation procedure when comparing first and second serves. This prevents us from directly comparing our results with existing literature. Regardless of serve type, inspection of activation levels for the three normalisation procedures revealed that no single method is best for eliciting systematically higher or lower EMG levels. For instance, while MVC recorded higher

Table 1. Results of statistical analysis.

Variables	MVC		SJ		SERVE		Kruskall Wallis *P* value (η^2) [Cohen's *d*]	
(au)	First serve	Second serve	First serve	Second serve	First serve	Second serve	Normalization method	Service type
Left leg								
EMG_{VL}	0.815 ± 0.871	0.647 ± 0.593	0.724 ± 0.574	0.565 ± 0.296	0.496 ± 0.153	0.394 ± 0.110	0.206 (0.03) [0.36]	0.092 (0.04) [0.43]
EMG_{RF}	0.481 ± 0.301	0.418 ± 0.212	0.542 ± 0.269	0.442 ± 0.346	$0.289 \pm 0.237^{*\#}$	$0.214 \pm 0.164^{*\#}$	**0.005 (0.32) [1.38]**	0.132 (0.01) [0.20]
EMG_{GL}	0.927 ± 0.733	0.801 ± 0.518	0.745 ± 0.617	0.629 ± 0.424	0.562 ± 0.100	0.485 ± 0.123	0.309 (0.01) [0.23]	0.214 (0.01) [0.23]
EMG_{SOL}	0.992 ± 0.967	0.828 ± 0.842	0.660 ± 0.403	0.536 ± 0.209	$0.287 \pm 0.197^{*\#}$	$0.226 \pm 0.149^{*\#}$	**0.001 (0.79) [3.82]**	0.308 (0.04) [0.38]
Right leg								
EMG_{VL}	0.643 ± 0.538	0.462 ± 0.319	0.678 ± 0.298	0.465 ± 0.145	0.507 ± 0.203	0.362 ± 0.163	0.299 (0.02) [0.25]	**0.014 (0.15) [0.84]**
EMG_{RF}	0.904 ± 0.724	0.713 ± 0.691	0.506 ± 0.268	0.370 ± 0.232	0.406 ± 0.144	0.306 ± 0.131	0.132 (0.08) [0.57]	0.081 (0.04) [0.40]
EMG_{GL}	0.933 ± 0.556	0.846 ± 0.769	$0.499 \pm 0.139^{*}$	$0.425 \pm 0.162^{*}$	$0.417 \pm 0.198^{*}$	$0.355 \pm 0.204^{*}$	**0.001 (0.42) [1.71]**	0.216 (0.02) [0.27]
EMG_{SOL}	0.490 ± 0.308	0.436 ± 0.231	0.766 ± 0.694	0.576 ± 0.336	$0.360 \pm 0.222^{\#}$	$0.279 \pm 0.131^{\#}$	**0.012 (0.25) [1.16]**	0.231 (0.02) [0.29]

Surface electromyography activity (EMG) for four muscles (vastus lateralis [VL], rectus femoris [RF], gastrocnemius lateralis [GL] and soleus [SOL]) of the left and right leg was normalised to maximal activity measured during isometric maximal voluntary contractions (MVC) and squat jump (SJ) as well as peak values obtained during actual tennis serves (SERVE).
Kruskal–Wallis test for normalization method and service type are stated along with partial-eta squared (η^2)and [Cohen's d].
* significantly different from MVC ($P < 0.05$); # significantly different from SJ ($P < 0.05$)..

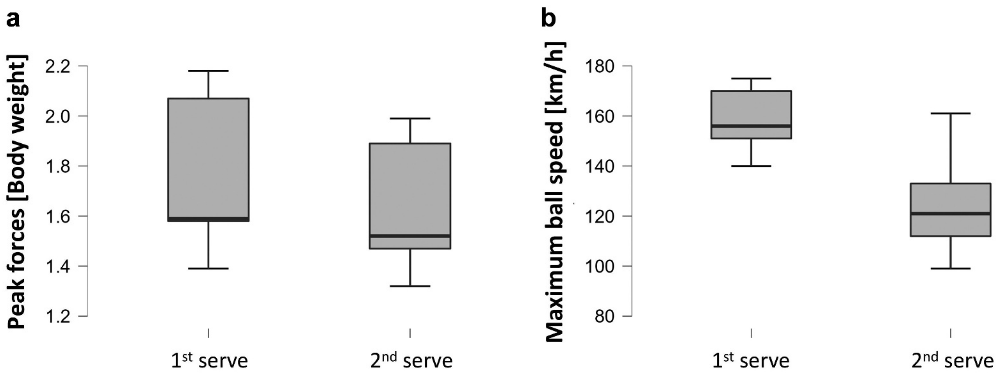

Figure 2. Peak vertical forces (in body weight; (a) and maximum ball speed (in km/h; (b) during first and second tennis serves (1st serve and 2nd serve, respectively).

values for right RF, left SOL, left GL, and right GL, readings for left RF and right SOL were lower compared to other methods. Our initial hypothesis was only partially supported by these observations. While leg muscles on both sides showed stronger activation during the fastest serve, the comparison of ballistic and isometric tasks did not consistently result in higher or lower EMG values. The discrepancies in joint angles and muscle contraction speed likely explain why the three normalisation methods yielded different EMG values, indicating that neither the isometric (MVC) nor dynamic (SJ) normalisation methods provide a true representative measure of muscle activation during the serve. In interpreting EMG signals, it can not be excluded that cross-talk between some muscles may have affected our results; *i.e*., for instance, RF and SOL have the potential to collect signals from the large signal-generating *vastus intermedius* and the more superficial *gastrocnemii*, respectively (Farina et al., 2004). Overall, larger differences generally occur when comparing MVC with either SJ or SERVE, yet with no systematic directions (i.e., higher or lower EMG values) for such comparisons.

Differences between first and second serves

All muscles had higher numerical EMG values for first than second serve. Nonetheless, out of eight studied muscles, this difference was only significant for the right VL muscle. This reinforces that to produce faster ball velocity both knee extensors and plantar flexors in general needs to be more strongly activated. As expected, there was a reduction in maximum ball velocity from first to second serves (Dossena et al., 2018). One unique finding in our study based on GRF recordings was a decrease in the magnitude of peak vertical forces, albeit in a smaller and non-significant manner, from the first to the second serve. This implies that other neuro-mechanical factors not measured here that are directly related (i.e., plantar loading; Girard et al., 2010) or not (i.e., body positions to get more spin on second serves; Elliott et al., 1995) to a forceful leg drive, probably contributed to the difference in maximum ball velocities between the two types of serve. In support of this finding, analysis of plantar loading using pressure insoles indicated lower mean and peak pressures as well as maximal forces under the lateral forefoot of the front foot from first to second serves (Girard et al., 2010). Another important consideration may limit the generalisation of our findings to other serve actions. In our study, serves were hit in a target area bordering the 'T' of the right service box. Consequently, the difference in the magnitude (and timing) of peak muscle activity levels of both the front and rear legs, when targeting different zones (i.e., hitting down the line *vs*. cross-court) and/or serving from the 'ad' or left service court, should not be overlooked.

Individual responses

Even in players deemed to have homogeneous expertise levels and service skills, considerable EMG activity differences occurred. In particular, when normalising EMG data of tennis serve relative to values obtained from MVCs, activation levels for some participants largely exceeded 100% activation. In those cases, the constraint normalisation method elicited an activation less than that of the activity being investigated. One potential explanation for substantial variability is the fact that participants assumed an individualised stance somewhere between the foot-up and foot-back techniques. They did so to execute the serve motion as naturally as possible, depending on their preference, physical and technical characteristics, as well as their style of play. Previously, we recorded a higher relative load on the lateral mid-foot of the rear foot and on the front lateral forefoot in foot-up compared with foot-back service style (Girard et al., 2010). From the present experimental design, however, we were not able to evaluate how different serve stances may have influenced EMG values. Furthermore, we did not specifically assess the intra-/inter-individual reliability of normalised EMG values from each normalisation method, which may ultimately depend on the type of muscle action (Carpentier et al., 1999). Consequently, in our study, it is not possible to determine whether one method improves the reliability of detecting muscle activation during the serve. Further research is needed to address this aspect. Finally, the training background of tested individuals in this study did not permit generalisation of findings beyond trained/developmental tennis players. Making the distinction between a general trend drawn from the group mean of all tested players and the diversity of the EMG patterns that can be found within a particular individual is paramount when quantifying lower limb activity during the serve.

Limitations and additional considerations

This study is not without limitations. First, peak EMG amplitude was determined regardless of when (i.e., within a specific phase of the movement) it was achieved during the service execution. Despite similar studies focusing on lower extremities, lower trunk muscle activity is known to vary substantially during different phases of the serve Chow et al. (2009). Perhaps our comparison of three normalisation methods may have led to different results if specific phases of the serve were considered. Second, for all participants, joint angles were standardised for both isometric and dynamic contractions. It can not be excluded that results may have differed, for instance, if other unconstraint tests (i.e., countermovement jumps that include a stretch-shortening cycle) were included or if participants performed MVCs at their optimal muscle length (i.e., an angle likely maximising neural drive to active musculature) (Suydam et al., 2017). Regardless of the method used, maximal force (MVC) or power (SJ) production ultimately depends on the participant's willingness to provide a maximum effort. In our study, the coefficient of variation for successive MVC and SJ trials was < 5%. During the tests, participants were verbally encouraged to produce maximal efforts, and there was a 1-min rest period between trials to reproduce maximal performance. Nonetheless, maximal effort during MVC tests could only be confirmed by the use of the twitch interpolation technique, as previously done in tennis (Girard et al., 2008). Finally, it is important to note that a limitation of our study is the absence of *a priori* sample size calculation. Additionally, our sample size comprised only ten participants. However, given that a within-subject design was used, the relatively small sample size should not significantly impact the major findings of this study.

Practical implications

Three EMG normalisation techniques based on peak/maximal activity measured during MVC of knee extensors/plantar flexors, SJ, and the actual serve were compared between the first and second serves. Regardless of serve type, there was a noticeable variation in the trend of the EMG activity across all normalisation methods. This implies that EMG activation levels should not be directly compared between different normalisation methods. The impact of the EMG normalisation procedure on muscle activation levels did not differ between the first and second serves, with generally lower values for the latter. While the present EMG data provide reference data, these values should not be used as electromyographical landmarks to determine lower limb muscle activity for all tennis players, as these values ultimately are both population- (i.e., males only) and performance-level-specific (i.e., competitive players). Considering the large inter-individual variability, a suggestion going forward is to focus less on searching for universal lower limb EMG activity patterns during the serve and more on exploring the emergence of context-specific muscle recruitment strategies.

Conclusion

We compared the surface EMG activity of eight lower limb muscles during first and second serves across three normalisation methods. Our main finding was that the choice of the normalisation method influences EMG activity levels. Specifically, it affects RF and SOL muscles in the left leg and GL and SOL muscles in the right leg. Collectively, all three EMG activity normalisation methods offer similar information regarding lower limb muscle activity (at least for investigated knee extensor and plantar flexor muscles) when comparing first and second serves. This new information could improve reporting on muscle activation levels and be used as a tool with considerable interests for tennis professionals.

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