Citation:
Bissas, A and Walker, J and Paradisis, GP and Hanley, B and Tucker, CB and Jongerius, N and Thomas, A and Merlino, S and Vazel, P and Girard, O (2022) Asymmetry in sprinting: an insight into sub10 and sub11 s men and women sprinters. Scandinavian Journal of Medicine & Science in Sports, 32 (1). pp. 69-82. ISSN 0905-7188 DOI: https://doi.org/10.1111/sms.14068

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Document Version:
Article (Accepted Version)

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Article type : Original Article

Asymmetry in sprinting: an insight into sub-10 and sub-11 s men and women sprinters

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Short title: Mechanical asymmetry in elite sprinters
Submission type: Original Investigation
Word count: 2975

Abstract

We evaluated sprint mechanical asymmetry in world-class competitors and evaluate whether inter-limb sex-based differences in sprinting mechanics exist. The eight finalists in the men's and women's 100 m events at the 2017 IAAF World Championships were studied. Five high-speed cameras (150 Hz) were used to capture two consecutive steps of the whole body between 47.0 m and 55.5 m from the start, while four additional cameras (250 Hz) focussed on the lower extremities. A total of 33 spatio-temporal, touchdown and toe-off joint angles, and horizontal and vertical foot velocity parameters were extracted through three-dimensional analysis. Group mean asymmetry scores were assessed using the symmetry angle (SA) where scores of 0% and 100% represent perfect symmetry and perfect asymmetry, respectively. Although considered generally low (SA < 3% for 22 out of 33 parameters), the magnitude of mechanical asymmetry varied widely between sprinters of the same sex. However, there was no mean SA scores difference between men and women for any stride mechanical parameters (all P≥0.064). Asymmetry scores were inconsistent between parameters and phases (touchdown vs toe-off instants), and sprinting mechanics were generally not related to asymmetry magnitudes. In summary, low to moderate asymmetry is a natural phenomenon in elite sprinting. Asymmetry was inconsistent between parameters and competitors during near maximum-velocity running, yet mean values for a given parameter generally did not differ between sexes. Sprinters' performances were not related to their SA scores.

Key words: symmetry angle scores; sprint running; running mechanics; sex differences; World Championships.

1. Introduction

A major preoccupation for sports scientists and elite coaches has always been a better understanding of the biomechanical factors within a stride in record holders and World Champions. Studying some of the fastest sprinters in the world during major official competitions therefore represents a unique opportunity to explore the limits of human locomotor performance.[1]

Such a study of sprinting, however, would be considered incomplete if it ignored the bipedal nature of this form of locomotion. Bilateral asymmetry is an observed difference in kinetic or kinematic gait parameters between the right and left sides of the body,[2] and has been the topic of recent sprint running investigations but in sub-elite sprinters only.[3,4] Quantifying the degree of stride mechanical asymmetry can assist in the prescription of appropriate interventions to eventually improve sprinting, reduce injury risk and predict reinjury to the lower extremity.[5,6]

The consequences of an uneven stride on sprint performance is still a controversial issue.[3,4,7,8] Apart from the lack of asymmetry data on world-class sprinters in action, a further critical limitation of available literature on sprinting asymmetry includes biomechanical evaluations performed on instrumented treadmills as opposed to over-ground conditions.[9,10] An additional challenge is that several methods employed for asymmetry calculation (i.e., limb symmetry index or ratios of asymmetry between left and right limbs) require a reference value and suffer from artificial inflation.[6] The symmetry angle (SA), a dimensionless measure to quantify asymmetry,[2] was therefore developed as an alternative and adopted in recent sprint running studies.[9,10]

A further gap in existing literature is that no authors have addressed the effect of sex on the magnitude of asymmetry in sprinting, although previous studies have identified several biomechanical causes for reaching a lower maximum sprinting velocity in women than men.[11] Therefore, our knowledge and understanding of the biomechanics of sprinting asymmetry is currently incomplete as it is lacking key pieces of information derived from performances, from both sexes, approaching maximal human velocity. The design of an experiment to capture the highest running velocity across the human race and analyse its parameters is plausibly impossible. However, the capturing of kinematic data from the finalists of the 2017 World Athletics Championships including the world record holder for the men's 100 m and the world-leading men and women is proposed as the best alternative condition to investigate this issue. Such data capture which included a multi-camera set up and was followed by a three-dimensional (3D) analysis had never been performed previously nor been replicated since.

Therefore, this study provides an unprecedented insight into the mechanics of maximal human velocity of both sexes with a particular focus on mechanical asymmetry. Our original approach proposes, for the first time, a real-life benchmark for expected asymmetry scores in elite sprinters. Our study, due to the broader enquiry framework in which it was included, was exploratory in nature and aspired to generate authentic data from highly competitive conditions.

This new knowledge will have a direct impact on training and sports medicine practices by providing coaching and medical professionals with objective scientific data to base upon their evaluations and interventions.

2. Methods

21. Participants

Data were collected as part of the London 2017 World Championships Biomechanics Research Project [12,13] and the use of those data was approved by World Athletics, who control the data, and locally through the institution's research ethics procedures. The 100 m time (mean ± standard deviation) for the men finalists was 10.04 ± 0.12 s whilst for women 10.97 ± 0.09 s. Seven out of the eight men finalists (age: 26.1 ± 4.8 yrs) were already sub-10 s sprinters with the eighth sprinter having 10.03 s as personal best at the time of the competition, whilst all women finalists (age: 26.7 ± 2.0 yrs) were sub-11 s sprinters before this particular final. The 16 finalists in the men's and women's 100 m races were analysed in their respective races, on the evenings of 5th and 6th August 2017 at London Stadium, UK. The temperature, relative humidity and wind speed were 19°C, 49% and –0.8 m/s for the men's race and 19°C, 56%, +0.1 m/s for the women's race.

22. Data collection

Several locations for camera placement were identified and secured on the broadcasting balcony along the home straight (Figure 1). Five Sony PXW-FS7 cameras operating at 150 Hz (shutter speed: 1/1250 s; ISO: 1600; FHD: 1920×1080 px) were used to capture the motion of athletes as they moved through the calibrated middle section of the race (47.0 – 55.5 m). Furthermore, four Fastec TS3 cameras operating at 250 Hz (shutter speed: 1/1000 s; ISO: 1600; SXGA: 1280×1024 px) recorded within the same middle section volume by focusing on the lower body segments. A calibration procedure was conducted before and after each race. A rigid cubic calibration frame measuring 3.044 × 3.044 × 3.044 m and comprising 24 control points was used. It was sequentially positioned multiple times over discrete predefined areas along and across the track to ensure an accurate definition of a volume within which the athletes achieved high running velocities. This approach produced a large number of non-coplanar control points per individual calibrated volume and facilitated the construction of a local coordinate system in each neighbouring pair of lanes that was then combined into a global coordinate system.

23. Data processing

The video files were imported into SIMI Motion (SIMI Motion version 9.2.2, Simi Reality Motion Systems GmbH, Germany) and were manually digitised by a single experienced operator to obtain kinematic data. An event synchronisation technique (synchronisation of all cameras by using four independent instants, all visible within the field of view of each camera) was applied through SIMI Motion to synchronise the two-dimensional coordinates from each camera involved in the recording. Digitising started 15 frames before the beginning of the stride and completed 15 frames after to provide padding during filtering.[14] Each file was first digitised frame by frame and, upon completion, adjustments were made as necessary using the points over frame method.[15] Throughout the specified volume, 17 anatomical locations (centre of the head, left and right shoulder, elbow, wrist, metacarpo-phalangeal, hip, knee, ankle and metatarso-phalangeal joint centres) were fully digitised to create a whole-body centre of mass (CM) model, in accordance with de Leva.[16] The Direct Linear Transformation algorithm was used to reconstruct the three-dimensional (3D) coordinates from individual camera's x and y image coordinates.[17] The accuracy of the 3D reconstruction measured as a percentage of the number of pixels in the image was <1% for each camera. Reliability of the digitising process was estimated by repeating the process for specific variables for eight randomly selected athletes with an intervening period of 48 h. The results showed minimal total errors and therefore confirmed the high reliability of the digitising process (Table 1). A recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was employed to filter the raw coordinate data for the five joint centres digitised continuously throughout the movement. The cut-off frequency was calculated (mean 13.9 Hz, range 11.0–15.5 Hz) using residual analysis.[18] Finally, temporal kinematic characteristics were processed through SIMI Motion by the 250 Hz footage. Absolute agreement between two analysers was established for all temporal parameters. Comprehensive descriptions of all kinematic characteristics are presented in Table 2, and also found in Bissas et al. scientific reports.[12,13]

24. Symmetry angle

For each participant, inter-leg symmetry was measured using the symmetry angle[2] and rectified so that all values were positive.[3] The SA was calculated using the below equation[2]:

$$\text{Symmetry angle} = [45° - \arctan(X_{\text{Left}}/X_{\text{Right}})/90°] \times 100\%$$

where X_{Left} is the value for the left side and X_{Right} is the value for the right side. The SA is an arctan function of the ratio of two bilateral values, where a SA score of 0% indicates perfect symmetry and 100% indicates perfect asymmetry.

25. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 25.0 (SPSS Inc., Chicago, IL, USA). Mean and standard deviation values for all analysed variables are presented. Independent samples t-tests, with adjustments made if Levene's test for equality of variance was less than 0.05, were used to analyse differences in asymmetry between men and women sprinters. Effect sizes (ESs) for differences between groups were calculated using Cohen's d[19] and considered to be either trivial (ES: ≤ 0.20), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00) or very large (> 2.01). Furthermore, a two-way mixed analysis of variance (ANOVA) with repeated measures was used to test the main effects of phase (Touchdown [TD] vs Toe-off [TO]) and sex (Men vs Women) and any possible interaction between these factors on selected postural variables, with Greenhouse–Geisser correction used if Mauchly's test for sphericity was violated. Finally, Pearson's product moment correlation measures tested the strength of linear association between athletes' 100 m performance and SA scores. Statistical significance was accepted at the $P<0.05$ level.

3. Results

The first scenario encompasses step length, step velocity, horizontal distance to the CM (DCM) TO, ankle angle TO and CM horizontal velocity TD (Figure 2D, Figure 2G, Figure 2J, Figure 4C and Figure 5D). This scenario represents variables for which the mean (i.e., left and right legs) values differed between sexes (all $P\leq 0.011$), but the SA scores were consistent between men and women sprinters (all $P\geq 0.155$). The second, and most common scenario, represented all the other parameters that exhibited no differences for SA scores (all $P\geq 0.064$) and mean values (all $P\geq 0.066$) between sexes (Figures 2–6). For all sprinters (pooled values for males and females), differences for SA scores between TD and TO instants [$(X_{TO} - X_{TD})/X_{TO} \times 100$; where X_{TD} and X_{TO} are values for the touch-down and take-off instants, respectively] ranged from 4.0% to 93.0% across all variables. Particularly, the DCM TO SA was by 57% smaller than the DCM TD SA (2.2 ± 1.5 vs 5.2 ± 3.9%; $P<0.01$), whilst there was a remarkable difference (93.0%; $P<0.001$) for the thigh separation angle between TD (30.0 ± 26.4%) and TO (2.2 ± 1.8%).

Regarding noteworthy relationships, only one out of the 33 asymmetry variables studied in males and females was associated with performance. A significant correlation between asymmetry and sprint performance was found to exist for foot vertical velocity pre-TD (r=–0.86; P=0.006) in men and shank angle TD (r=0.81; P=0.016) in women.

4. Discussion

41. Asymmetry magnitude is parameter-dependent

Our observations provide an exclusive insight into the magnitude of mechanical asymmetry presented by world-class male and female sprinters during one of the most important global competitions. For the first time, we demonstrate that elite sprinters exhibit unique asymmetries for a set of pre-determined parameters deemed important by coaches,[20] although they had relatively even strides. A qualitative inspection of the mean bilateral asymmetries in men and women competitors indicates that scores can range from as low as 0.3% and 0.1% (CM horizontal velocity contact) and up to 36.0 and 24.2% (thigh separation angle TD), respectively. Previously, a wide range of kinetic SA values (~3% to 77%) was observed in a group of eight sprint-trained athletes, indicating drastically different variability between mechanical parameters during maximal velocity sprinting.[21] Direct comparisons of our asymmetry values with these previous findings are precluded by differences in performance standard of tested athletes (World-class vs sprint-trained individuals), calculation methods even for similar parameters, and/or the sprint phase considered (47.0 – 55.5 m vs 40 m from the start line). More importantly, our findings are one of a kind as they have been derived from a unique and truly ecologically valid setting and from the fastest men and women in the world who ran at velocities exceeding 11 and 10 m/s, respectively.

42. Sex-based differences in asymmetry

We found differences for step length, step velocity, DCM TO, ankle angle TO and foot vertical velocity pre-TD when nearing maximum running velocity between men and women sprinters. Of all parameters examined, however, none displayed different SA scores between sexes. Despite elite sprinters presenting a variety of body sizes and movement characteristics, they organise themselves similarly to optimise stride parameters that determine maximal sprinting velocity.[20] Overall, our results indicate that only subtle between-sexes differences exist regarding asymmetries for key sprinting parameters near maximal velocity.

43. Compensatory strategies

Inconsistencies between asymmetry of related biomechanical parameters among sprinters could result from natural compensatory strategies. This may in turn result from morphological specificities (e.g., limb length discrepancy), chronic strength weaknesses around some joints and/or imbalances in the range of motion at other joints.[22,23] Consequently, there is a possibility that asymmetrical limb stiffness could upset cyclical CM motion by causing an unstable running situation, when the sprinter is pushing each side to its limit, that could eventually degrade performance. In our study, though, there was a small amount of asymmetry for joint angles, similar to spatio-temporal parameters, but higher than for CM parameters. However, our analysis possibly exposed some key mechanical strategies in arranging body sides differently between the key instants of TD and TO. For a number of variables, with DCM and thigh separation angle being the most prominent, sprinters arranged their segments far more symmetrically at TO than TD. This was apparent in both sexes, yet with individual variations, and it is something requiring further monitoring in individual sprinters. There was no relationship between this trend and height or any other SA scores, but this observation poses a question around asymmetrical mechanical loading at TD with the possibility that such asymmetries over time could instigate and/or exacerbate musculoskeletal damages.

44. Individual responses

Individual athletes showed asymmetry for some, but not all, parameters tested here. In other words, asymmetry displayed in some parameters was not reflected with a corresponding degree of asymmetry in other parameters. For instance, the sprinter (male bronze medallist) with the highest SA scores for some parameters (e.g., contact time, step frequency, step velocity, DCM TD, foot horizontal velocity pre-TD) also had the lowest readings for others (e.g., ankle angle TO, CM height TD and TO). Interestingly, this particular sprinter, displayed the highest SA scores for DCM TD and thigh separation angle at TD, but one of the lowest scores for the same variables at TO, indicating that asymmetry is perhaps not only variable- but also phase-dependent.

In fact, the individual nature of mechanical asymmetry supports the notion of an athlete-specific step characteristic reliance, and thereby the necessity for individual analyses,[24] and research on sub-elite distance runners has similarly shown that being symmetrical in some gait variables, and asymmetrical in others, is normal for an individual athlete.[25] In support of the above, the men's final lined up two sprinters who produced remarkably extreme step lengths for sub-10 s sprinters: the longest steps for the bronze medallist with 2.70 m, and the shortest for the slowest athlete in the race with 2.26 m. It is therefore crucial to make the distinction between a general trend drawn from the eight finalists and the diversity of the features that can be found in particular sprinters.

45. Correlations

The possibility that sprint performance is linked with the degree of asymmetry has often been debated to decide whether or not attempts should be made to reduce asymmetries (i.e., strength and conditioning, technique adjustments) when there is a potential performance improvement. In a group of 32 Jamaican 100 m sprinters, Trivers et al.[26] reported that athletes with more symmetrical knees and ankles ran faster. Conversely, in line with previous findings,[4,7,8] we observed a lack of relationship between sprint performance and asymmetry magnitude in almost all mechanical parameters tested. Given the small sample size and the fact that whilst performance was represented by a global variable (100 m time) asymmetry was described by local step mechanical variables, any deep discussion regarding the dynamics of relationships including the only two significant (pre-TD velocity and shank angle at touchdown) correlations observed across our large matrix of 33 examined correlation pairs would be unwarranted.

Our original observations also add to the debate whether or not asymmetrical gait patterns during prosthetic use, for instance in Paralympic sprinters, negatively affects performance. Whereas using running-specific prostheses might enhance top speed by reducing the time required to reposition the leg,[27] others indicate that it limits ground-force and thus is a critical limitation for top speed.[28] Compared to non-amputee athletes, elite long jumpers with below the knee prostheses approach the board slower but take off more effectively, also with no difference in the overall vertical force from both legs and asymmetry levels within normal ranges for non-amputees.[29] Regardless, our results indicate that an asymmetry profile of able-bodied world-class sprinters cannot be derived from their race time.

46. Study strength and limitations

The major strength of this study is that it represents the first attempt to quantify asymmetries from sub-10 and sub-11 s men and women sprinters during the 100 m finals at an actual World Championships. The study's sample includes the fastest humans currently competing internationally and featuring the world record holders for the men's 60 m and 100 m. Inevitably this limits the sample size but having the World's best sprinters *in situ* in an elite competition environment provides an unprecedented study opportunity. Although data were obtained during the maximal-velocity sprint phase (i.e., between 47.0 and 55.5 m from the start), it should be noted that some sprinters, in particular men, are likely to still be accelerating at this stage. A further limitation relies in the fact that only one step per leg was considered to calculate SA scores. While it has been argued that asymmetry for a given parameter is meaningful only if the inter-limb variability exceeds the intra-limb variability,[21] our experimental set-up would only allow us to determine the former but not the later. Finally, in order to avoid the potential problem of anatomical landmark occlusion by other competitors in neighbouring lanes, our unique set-up with multiple cameras allowed us to always be able to see a particular moment of interest from at least two cameras (Figure 1).

5. Conclusion

Low to moderate asymmetry is a natural phenomenon in elite sprinting and overall sprinters' performance is generally not related to their asymmetry magnitudes. However, SA scores in biomechanical parameters of sprinting varied with the parameter, and at times with the phase, of interest, reinforcing the individual nature of asymmetry. Furthermore, sprinting mechanical asymmetries were largely unaffected by sex as it was evidenced in some of the fastest male and female sprinters in the world. Our results offer a novel benchmark for the expected magnitude of asymmetry in world-class sprinters during maximum-velocity sprinting and provide a basis of comparison for future studies.

6. Perspectives

Maximal velocity is limited by underlying kinetic capabilities rather than the kinematic motions that they produce.[30] Exell et al.[21] concluded that kinetic *vs*. kinematic SA scores were larger at maximal velocity, conjecturing that the neuromuscular system might be kinetically compensating in an attempt to minimise kinematic variability. In our study, SA scores were determined near maximal velocity only for kinematic variables as it was practically impossible to capture ground reaction forces during the World Championship finals. Future asymmetry studies should focus on the biomechanical parameters derived from direct measurement of ground reaction forces, recorded by a larger number of force plates laid in series,[31] during different phases of the sprint (i.e., acceleration, maximum velocity, and/or deceleration) for a more accurate interpretation of lower limb behaviour in relation to performance. These kinds of setups remain for now though a distant aspiration for official competitions as they would require radical changes in the rules of the sport and complex, costly technological applications.

Author contributions

AB, JW, GP, BH, CT, NJ, AT, and SM designed the experiments. AB, JW, GP, BH, NJ, AT, and SM collected data. AB, JW, GP, BH, CT, PJ V and OG analysed data. OG drafted the manuscript and all authors contributed to the final manuscript.

Conflicts of interest

The authors have no conflicts of interest that are relevant to findings of this manuscript. The results of the present study do not constitute endorsement by World Athletics. The use of the data for this study was approved by the IAAF (since renamed World Athletics), who own and control the data, and locally through institutional research ethics procedures.

Funding

The data collection and initial data analysis were supported by funding provided by *International Association of Athletics Federations* (since renamed World Athletics), as part of a wider development/education project; however, the nature of the data is purely descriptive and not associated with any governing body, commercial sector and product. No funding was provided for the writing of this article.

Data availability statement

Most of the data that support the findings of this study are openly available from World Athletics at: https://www.worldathletics.org/about-iaaf/documents/research-centre#collapse2017-iaaf-world-championships-biomechanics-st.

Additional data used for this article are available on request from the corresponding author.

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Figures legend

Figure 1 – Camera layout for the men's and women's 100 m events at the 2017 IAAF World Championships.

Figure 2 – Symmetry angle scores for spatio-temporal parameters in men and women sprinters. *Athletes are depicted with numbers in circles representing the order in which they crossed the finish line. Independent samples t-tests (and Cohen's d values) were used to analyse differences in asymmetry between men and women sprinters. DCM TD, the horizontal distance between the ground contact point (foot tip) at touchdown and the centre of mass; DCM TO, the horizontal distance between the ground contact point (foot tip) at toe-off and the centre of mass.*

Figure 3 – Symmetry angle scores for joint angles at touchdown (TD) in men and women sprinters.
Athletes are depicted with numbers in circles representing the order in which they crossed the finish line. Independent samples t-tests (and Cohen's d values) were used to analyse differences in asymmetry between men and women sprinters.

Figure 4 – Symmetry angle scores for joint angles at toe-off (TO) in men and women sprinters.
Athletes are depicted with numbers in circles representing the order in which they crossed the finish line. Independent samples t-tests (and Cohen's d values) were used to analyse differences in asymmetry between men and women sprinters.

Figure 5 – Symmetry angle scores for centre of mass (CM) excursion at touchdown (TD) and at toe-off (TO) in men and women sprinters.
Athletes are depicted with numbers in circles representing the order in which they crossed the finish line. Independent samples t-tests (and Cohen's d values) were used to analyse differences in asymmetry between men and women sprinters.

Figure 6 – Symmetry angle scores for horizontal and vertical foot velocity at touchdown (TD) in men and women sprinters. *Athletes are depicted with numbers in circles representing the order in*

which they crossed the finish line. Independent samples t-tests (and Cohen's d values) were used to analyse differences in asymmetry between men and women sprinters.

Table 1. Running mechanics for left (L) and right (R) leg in men and women finalists.

	Men			**Women**			**Men *vs.* Women**
	L or L/R	**R or R/L**	**Mean *(range)***	**L or L/R**	**R or R/L**	**Mean *(range)***	**P value**
Performance							
100-m sprint time (s)	-	-	10.04±0.12 *(9.92–10.27)*	-	-	10.97±0.09 *(10.85–11.09)*	–8.5% **(P<0.001)**
Reaction time (s)	-	-	0.155±0.033 *(0.123–0.224)*	-	-	0.168±0.021 *(0.142–0.200)*	–7.5% (P=0.374)
Personal best (s)	-	-	9.83±0.15 *(9.58–10.03)*	-	-	10.81±0.06 *(10.70–10.91)*	–9.1% **(P<0.001)**
Kinematics							
Contact time (s)	0.093±0.007	0.093±0.004	0.093±0.005 *(0.086–0.098)*	0.091±0.004	0.095±0.007	0.093±0.004 *(0.088–0.098)*	+0.0% (P=0.704)
Flight time (s)	0.115±0.010	0.118±0.007	0.116±0.007 *(0.108–0.130)*	0.115±0.011	0.117±0.008	0.116±0.004 *(0.108–0.122)*	+0.0% (P=1.000)
Step frequency (Hz)	4.84±0.29	4.77±0.21	4.80±0.21 *(4.40–5.00)*	4.86±0.22	4.74±0.29	4.80±0.13 *(4.62–5.00*)	+0.0% (P=1.000)
Step length (m)	2.42±0.15	2.43±0.14	2.42±0.14 *(2.25–2.69)*	2.16±0.08	2.18±0.10	2.17±0.08 *(2.07–2.30)*	+11.4% **(P<0.001)**
Step width (m)	0.18±0.05	0.19±0.06	0.19±0.05 *(0.12–0.24)*	0.15±0.06	0.14±0.07	0.14±0.06 *(0.04–0.23)*	+31.8% (P=0.127)
Step time (s)	0.208±0.014	0.210±0.009	0.209±0.010 *(0.200–0.208)*	0.206±0.009	0.212±0.013	0.209±0.006 *(0.200–0.218)*	+0.0% (P=1.000)
Step velocity (m/s)	11.65±0.19	11.56±0.33	11.60±0.17 *(11.28–11.84)*	10.52±0.40	10.33±0.40	10.43±0.25 *(9.88–10.67)*	+11.3% **(P<0.001)**
Swing-to-swing time (s)	0.211±0.010	0.215±0.012	0.213±0.010 *(0.204–0.232)*	0.214±0.011	0.212±0.009	0.213±0.006 *(0.204–0.222)*	+0.0% (P=1.000)
DCM TD (m)	0.38±0.07	0.37±0.04	0.38±0.04 *(0.32–0.44)*	0.37±0.04	0.37±0.05	0.37±0.02 *(0.33–0.39)*	+1.8% (P=0.691)
DCM TO (m)	0.63±0.05	0.60±0.05	0.61±0.04 *(0.57–0.68)*	0.50±0.05	0.52±0.04	0.51±0.04 *(0.47–0.59)*	+20.7% **(P<0.001)**
Angles touchdown (TD)							
Hip angle TD (º)	140.1±6.7	139.3±6.2	139.7±5.0 *(129.6–145.7)*	142.4±8.0	141.9±7.0	142.2±6.8 *(131.0–150.0)*	–1.7% (P=0.428)
Knee angle TD (º)	159.6±6.3	153.4±7.8	156.5±6.1 *(147.7–167.1)*	159.0±5.8	151.0±5.3	155.0±4.1 *(148.2–161.5)*	+1.0% (P=0.561)
Ankle angle TD (º)	119.2±4.0	113.5±4.1	116.4±3.0 *(110.0–119.3)*	120.6±3.9	116.0±5.0	118.3±2.4 *(113.7–120.8)*	–1.7% (P=0.162)
Shank angle TD (º)	100.5±4.4	96.8±3.2	98.7±3.5 *(92.9–103.7)*	99.4±4.7	96.9±1.0	98.1±2.4 *(95.0–104.0)*	+0.5% (P=0.734)
Thigh angle TD (º)	26.5±5.4	28.2±5.3	27.4±4.7 *(20.5–35.2)*	27.3±3.8	32.0±4.6	29.7±3.6 *(22.8–34.5)*	–7.7% (P=0.292)
Thigh separation angle TD (º)	-9.1±13.0	-10.7±11.7	-9.9±10.7 *(-27.4–-1.6)*	-14.7±12.3	-21.2±11.6	-18.0±10.3 *(-28.7–0.6)*	–44.9% (P=0.146)
Trunk angle TD (º)	75.1±4.3	75.8±2.7	75.5±3.0 *(71.4–80.4)*	79.6±5.6	79.0±3.8	79.3±4.6 *(72.5–86.3)*	–4.8% (P=0.066)
Angles toe-off (TO)							
Hip angle TO (º)	196.9±4.1	195.6±4.5	196.3±2.9 *(192.3–201.0)*	200.1±7.7	196.5±8.3	198.3±7.4 *(186.8–209.2)*	–1.0% (P=0.480)
Knee angle TO (º)	154.4±3.4	152.6±6.7	154.0±4.2 *(145.7–157.8)*	150.4±11.7	152.8±5.0	151.6±8.2 *(142.0–163.2)*	+1.6% (P=0.470)
Ankle angle TO (º)	141.0±6.7	135.4±5.2	138.2±3.5 *(134.1–144.1)*	133.8±6.0	128.3±7.7	131.0±6.0 *(122.4–139.6)*	+5.5% **(P=0.011)**
Shank angle TO (º)	38.8±2.0	39.2±2.2	39.0±1.4 *(36.1–40.5)*	39.7±3.3	39.8±2.6	39.8±2.2 *(36.7–42.6)*	–2.1% (P=0.400)
Thigh vertical angle TO (º)	-26.8±2.5	-23.6±5.3	-25.2±3.1 *(-29.0–-19.7)*	-22.4±9.6	-23.2±4.5	-22.8±6.8 *(-34.4–-15.4)*	+10.4% (P=0.387)
Thigh separation angle TO (º)	94.6±8.3	91.6±7.7	93.1±7.3 *(81.6–104.7)*	86.7±11.6	89.1±4.3	87.9±7.4 *(79.0–95.8)*	+5.8% (P=0.178)
Trunk angle TO (º)	80.8±3.5	80.7±3.4	80.7±3.2 *(75.6–84.8)*	82.6±4.6	83.6±3.3	83.1±3.3 *(78.2–86.9)*	–2.8% (P=0.173)
Centre of mass (CM) excursion							
CM height TD (m)	0.97±0.06	0.97±0.06	0.97±0.06 *(0.91–1.09)*	0.93±0.03	0.93±0.03	0.93±0.03 *(0.89–0.98)*	+3.9% (P=0.146)
CM height minimum (m)	0.96±0.06	0.96±0.06	0.96±0.06 *(0.90–1.07)*	0.92±0.03	0.92±0.03	0.92±0.03 *(0.88–0.97)*	+3.9% (P=0.141)
CM height TO (m)	1.00±0.06	1.00±0.06	1.00±0.06 *(0.94–1.12)*	0.95±0.03	0.95±0.03	0.95±0.03 *(0.91–1.00)*	+5.0% (P=0.066)

CM horizontal velocity (m/s)	11.61±0.14	11.55±0.11	11.58±0.12 *(11.35–11.75)*	10.45±0.13	10.45±0.13	10.45±0.13 *(10.21–10.61)*	+10.9% **(P<0.001)**
Foot velocity							
Foot horizontal velocity pre-TD (m/s)	3.23±0.41	3.37±0.93	3.30±0.58 *(2.59–4.47)*	2.99±0.99	2.94±0.41	2.96±0.53 *(2.15–3.58)*	+11.4% (P=0.246)
Foot horizontal velocity TD (m/s)	2.30±0.38	2.42±0.75	2.36±0.47 *(1.69–3.23)*	2.02±0.66	2.14±0.41	2.08±0.41 *(1.50–2.60)*	+13.5% (P=0.215)
Foot vertical velocity pre-TD (m/s)	-3.20±0.40	-3.13±0.40	-3.16±0.32 *(-3.59–-2.59)*	-2.96±0.32	-3.04±0.37	-3.00±0.26 *(-3.35–-2.68)*	+5.4% (P=0.298)
Foot vertical velocity TD (m/s)	-2.51±0.49	-2.44±0.48	-2.47±0.35 *(-2.86–-1.76)*	-2.26±0.31	-2.40±0.38	-2.33±0.24 *(-2.65–-1.95)*	+6.2% (P=0.355)
Peak vertical velocity swing (m/s)	7.62±1.17	7.36±1.30	7.49±1.18 *(5.16–8.85)*	7.03±0.97	6.92±1.15	6.97±0.99 *(4.98–7.80)*	+7.4% (P=0.357)

Values are Mean±SD (range).
[*] *significantly different between men and women ($P<0.05$).*

CONTACT TIME, the time the foot is in contact with the ground; FLIGHT TIME, the time from toe-off (TO) of one foot to touchdown (TD) of the other foot; STEP TIME, Contact time + Flight time; STEP FREQUENCY, the number of steps per second – calculated as the reciprocal of step time; STEP LENGTH, the distance covered from TO on one foot to TO on the other foot; STEP WIDTH, mediolateral distance between two consecutive foot contacts (foot tips); STEP VELOCITY, running velocity over one step (step length/step time); SWING-TO-SWING TIME, the time from TO of one foot to TO of the other foot (airborne to airborne); DCM TD, the horizontal distance between the ground contact point (foot tip) at TD and the CM; DCM TO, the horizontal distance between the ground contact point (foot tip) at TO and the CM.

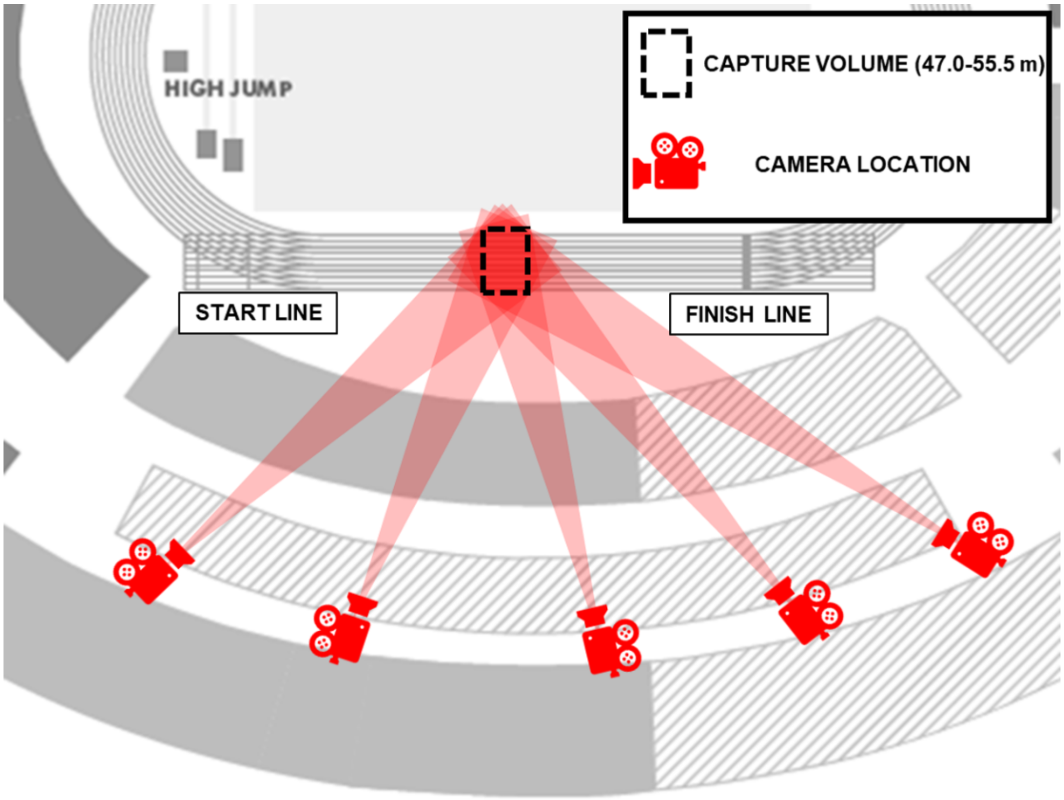
HIP ANGLE, the shoulder-hip-knee angle and considered to be 180° in the anatomical standing position; KNEE ANGLE, the angle between the thigh and lower leg and considered to be 180° in the anatomical standing position; ANKLE ANGLE, the angle between the lower leg and the foot and considered to be 90° in the anatomical standing position; SHANK ANGLE, the angle of the lower leg relative to the running surface and considered to be 90° when the shank is perpendicular to the running surface; THIGH ANGLE, the angle between the thigh of the contact leg and the vertical (positive values indicate that the thigh segment was in front of the vertical axis whereas negative values indicate the thigh found positioned behind the vertical axis); THIGH SEPARATION ANGLE, the angle between the thighs of the contact and swing legs (a negative value indicates that the swing leg is behind the touchdown leg in the sagittal plane at the point of contact, whereas a positive value indicates the swing thigh is in front of the contralateral thigh segment); TRUNK ANGLE, the angle of the trunk relative to the horizontal and considered to be 90° in the upright position. For Hip, Knee and Ankle angles, higher values indicate a more extended joint position.

CM HEIGHT, vertical distance between the CM and the running surface during ground contact; CM HEIGHT MINIMUM, the lowest vertical distance between the CM and the running surface during ground contact; CM HORIZONTAL VELOCITY, Mean horizontal CM velocity over one step (calculated through full-body digitizing).

FOOT HORIZONTAL VELOCITY, the horizontal component of the foot CM velocity (positive velocities observed indicate that the foot is moving forwards relative to the running surface); FOOT VERTICAL VELOCITY, the vertical component of the foot CM velocity (negative velocities observed indicate the downward movement of the foot CM); PEAK VERTICAL VELOCITY SWING, the peak vertical velocity of the foot CM during the air phase.

Table 2. Test-retest reliability for all variables.

	Test-retest (48 hours)	
	ICC$_{3,1}$	**RMSD**
Kinematics		
Contact time (s)	1.000	=0.000
Flight time (s)	1.000	=0.000
Step frequency (Hz)	1.000	=0.00
Step length (m)	0.999	0.01
Step width (m)	0.980	0.01
Step time (s)	1.000	=0.000
Step velocity (m/s)	0.996	0.05
Air time (s)	1.000	=0.000
DCM TD (m)	0.999	<0.01
DCM TO (m)	>0.999	<0.01
Angles touch down (TD)		
Hip angle TD (º)	0.996	0.6
Knee angle TD (º)	0.990	0.9
Ankle angle TD (º)	0.933	1.8
Shank angle TD (º)	0.992	0.6
Thigh angle TD (º)	0.996	0.5
Thigh separation angle TD (º)	0.998	0.7
Trunk angle TD (º)	0.999	0.2
Angles take off (TO)		
Hip angle TO (º)	0.996	0.6
Knee angle TO (º)	0.996	0.9
Ankle angle TO (º)	0.985	1.1
Shank angle TO (º)	0.988	0.5
Thigh vertical angle TO (º)	0.999	0.4
Thigh separation angle TO (º)	0.999	0.5
Trunk angle TO (º)	0.999	0.2
Centre of mass (CM) excursion		
CM height TD (m)	>0.999	<0.01
CM height minimum (m)	>0.999	<0.01
CM height TO (m)	0.943	0.02
CM horizontal velocity (m/s)	>0.999	0.01
Foot velocity		
Foot horizontal velocity pre-TD (m/s)	0.998	0.04
Foot horizontal velocity TD (m/s)	0.999	0.02
Foot vertical velocity pre-TD (m/s)	0.995	0.04
Foot vertical velocity TD (m/s)	>0.999	<0.01
Peak vertical velocity swing (m/s)	>0.999	0.02



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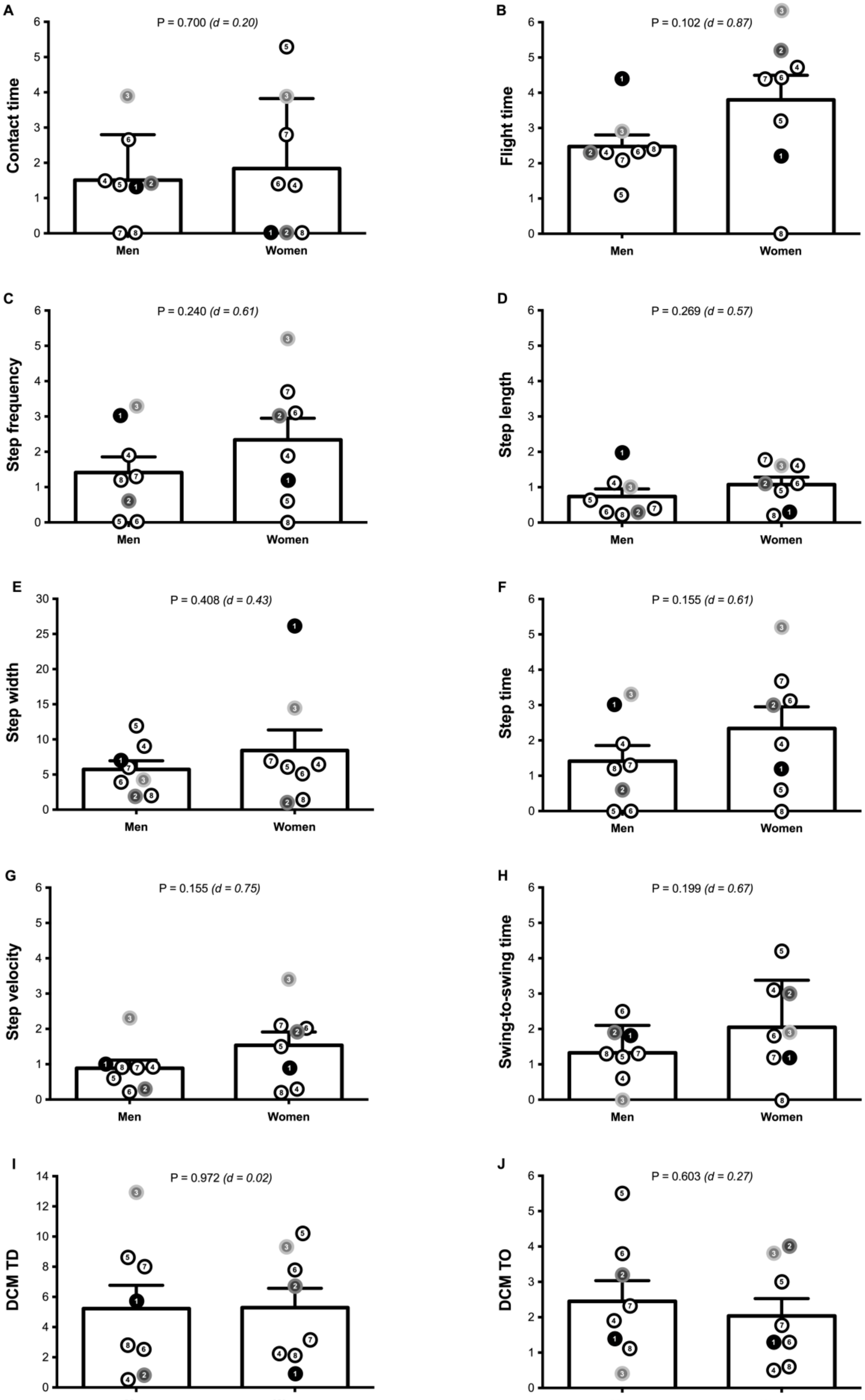

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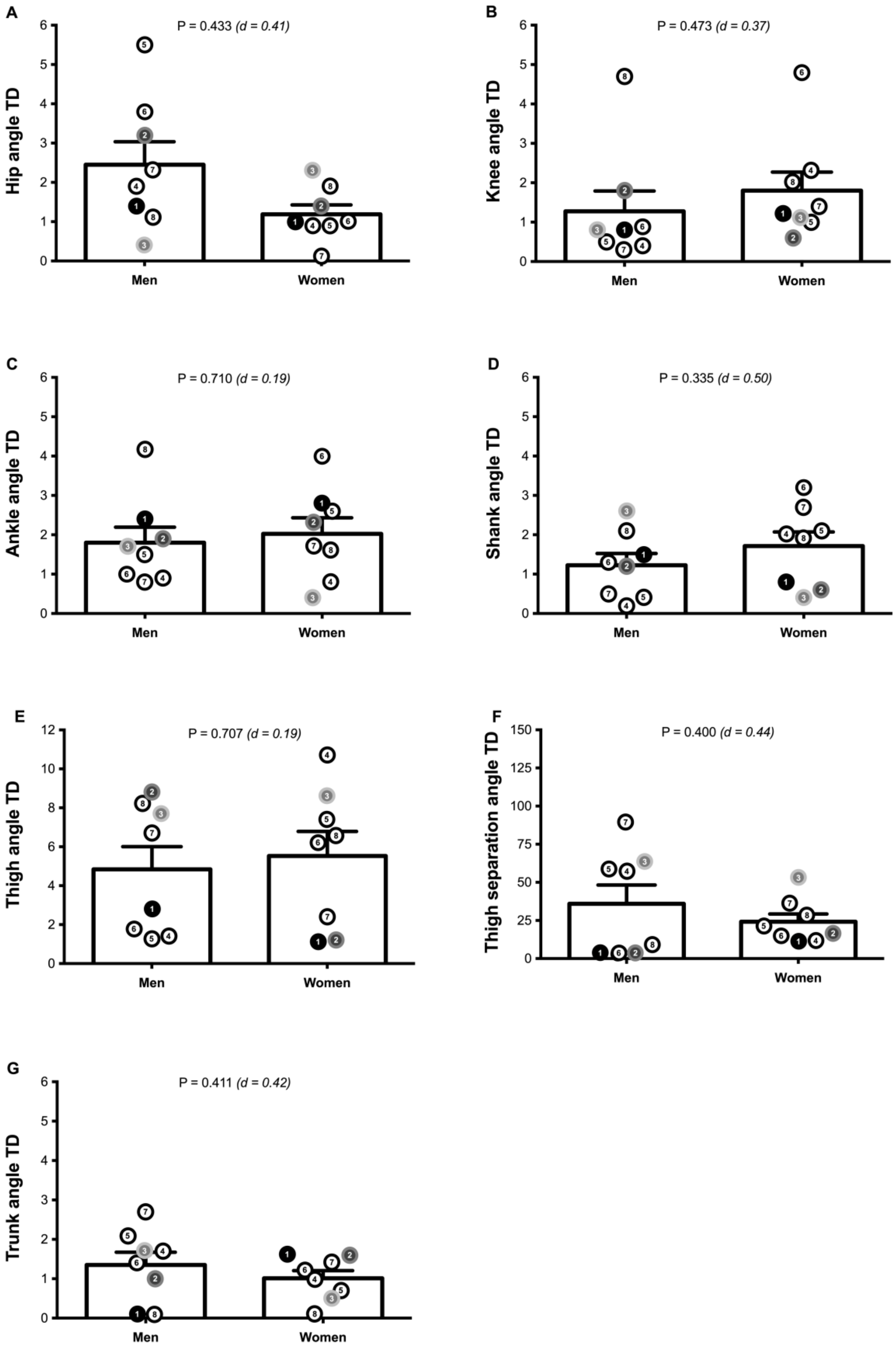

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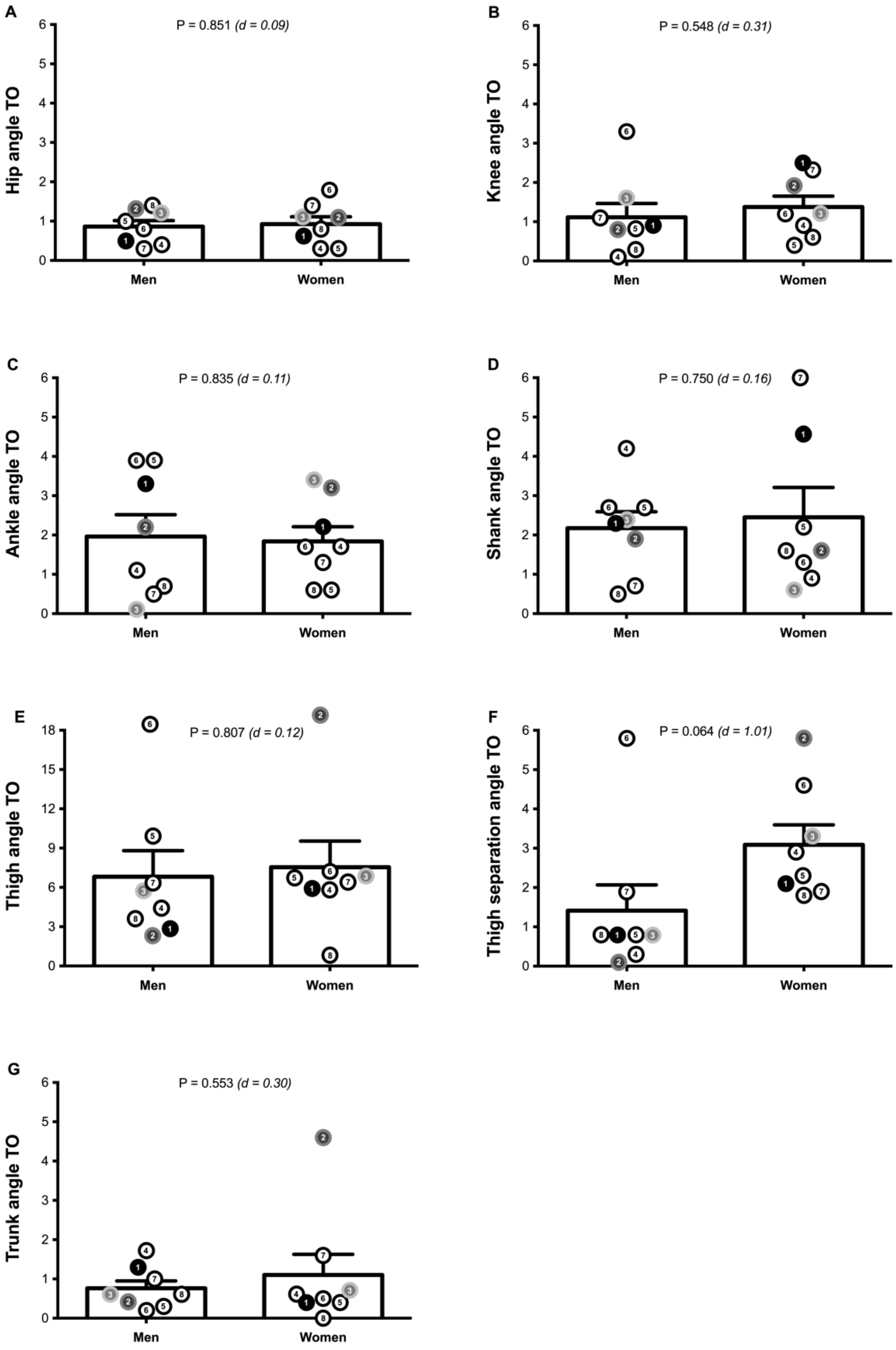

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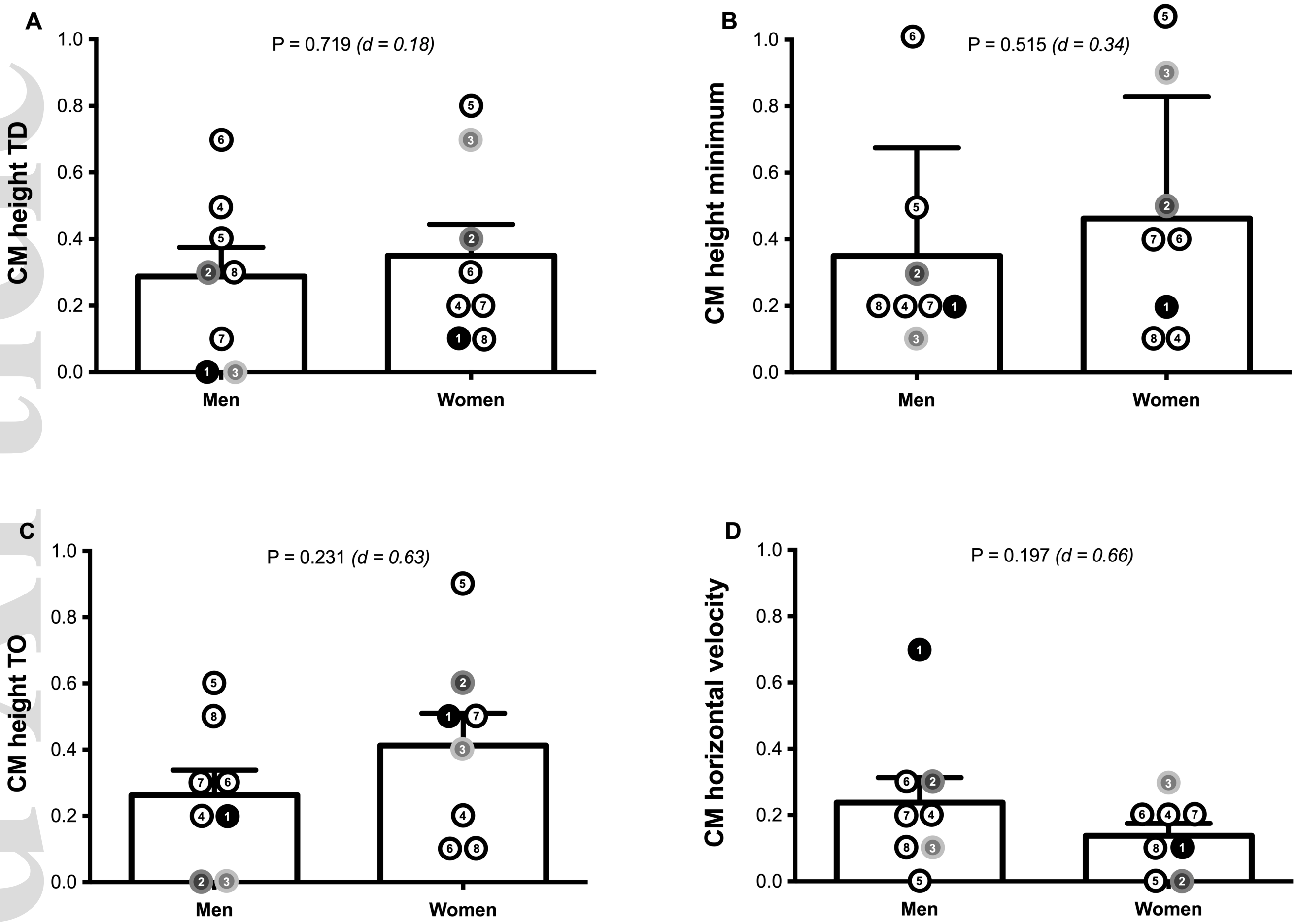

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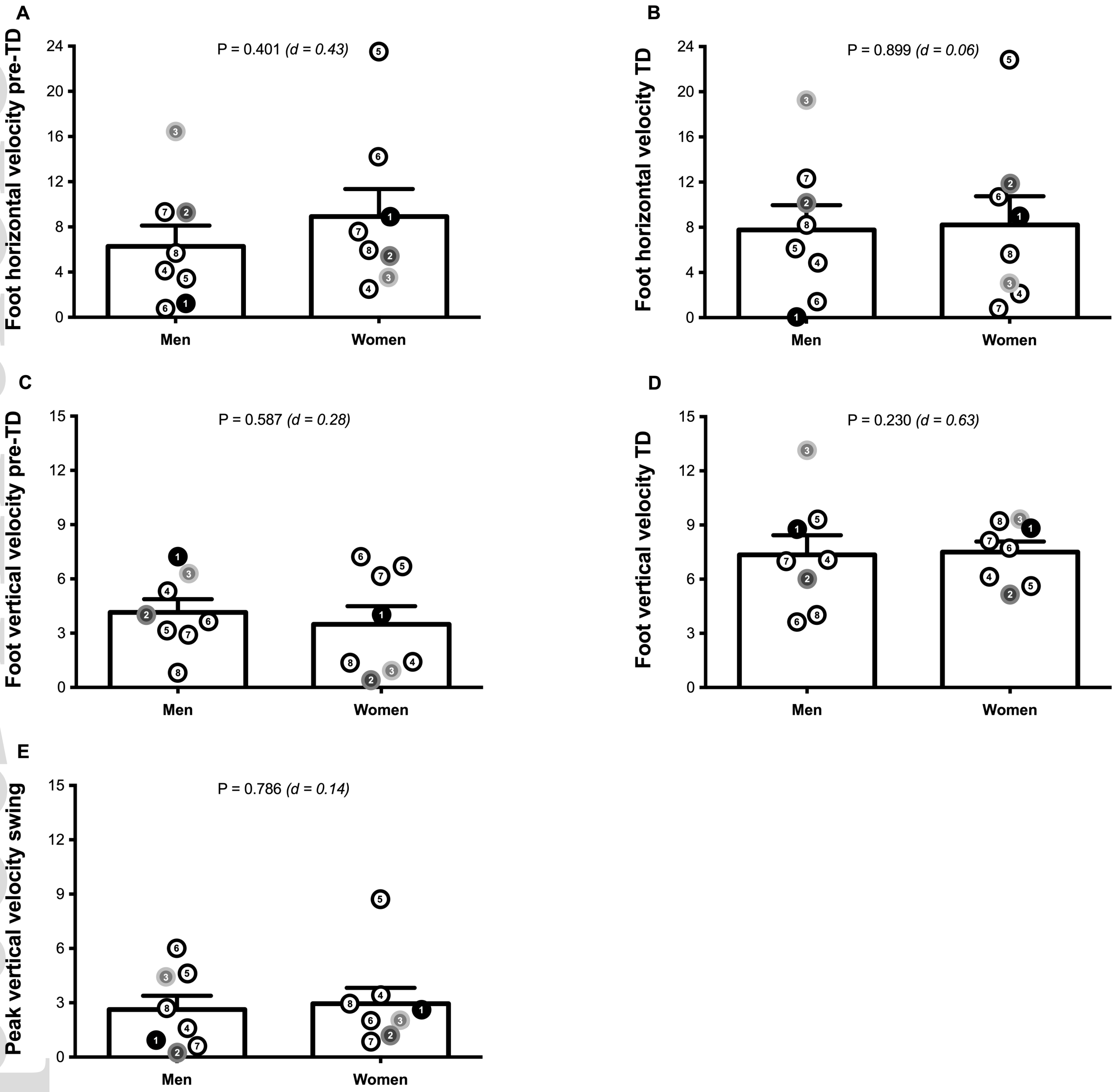

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