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MEASUREMENT OF BEND SPRINTING KINEMATICS WITH THREE-DIMENSIONAL MOTION CAPTURE: A TEST-RETEST RELIABILITY STUDY

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Abstract

Sprint velocity decreases on the bend when compared with the straight, therefore understanding technique during bend sprinting could have important implications for aiding race performance. Few bend sprinting studies have used optoelectronic cameras to investigate kinematic variables. Limited published evidence regarding the reliability of marker sets in conditions representative of elite bend sprinting makes model selection difficult. Therefore, a test-retest protocol was conducted to establish the reliability and minimum detectable difference of a lower limb and trunk marker set during bend sprinting (radius: 36.5 m). Six participants completed five, 60 m trials at maximum effort, with data collected at 38 - 45 m. This was repeated 2 - 7 days later. Spatio-temporal (e.g. contact time) and kinematic variables (e.g. peak joint angles) were evaluated. Intraclass correlation coefficients (ICC) were used to determine the between- and within-day reliability. Between-day reliability (ICC 3, *k*) was fair to excellent for all variables. Compared to between-day, within-day reliability demonstrated stronger agreement for the majority of variables. Thus, same-day data collection is preferable. It has been established that the marker set is reliable for future use. In addition, the minimal detectable difference was calculated which serves as useful reference for future research in bend sprinting. (Word count: 200)

Key words: 200 m, three-dimensional, athletics, curve, joint angles

Introduction

Sprint velocity decreases on the bend in comparison to the straight (Chang & Kram, 2007; Churchill, Salo, & Trewartha, 2015; Churchill, Trewartha, Bezodis, & Salo, 2016). This reduction is suggested to be related to the additional need to generate centripetal force (Chang & Kram, 2007; Usherwood & Wilson, 2006). Unlike the 100 m race that occurs entirely on the straight, the 200 m and 400 m races include a portion on the bend that accounts for approximately 58% of the total distance covered (Meinel, 2008). Therefore, performance on the bend makes a substantial contribution to overall race performance.

Whilst there has been some consideration of the reliability of sprint related performance variables within the literature (most notably Hunter, Marshall & McNair, 2004a; Salo & Grimshaw, 1998; Standing & Maulder, 2017), the analysis of performance descriptors has been the main focus. However, substantial adaptations in joint kinematics have been reported during bend sprinting in comparison to straight line sprinting (e.g. Churchill et al., 2015, Alt, Heinrich, Funken, & Potthast, 2015), without supporting reliability data it is difficult to determine whether these changes have been influenced by variation in task execution, equipment calibration, random error or protocol design.

To evaluate performance on the bend, the analysis of spatio-temporal, kinematic and kinetic variables is required. Owing to its high reliability and validity, data collection with optoelectronic systems is considered the gold standard of kinematic measurement techniques (Hood, McBain, Portas, & Spears, 2012). Despite this, few bend sprinting studies have used optoelectronic cameras to investigate kinematic variables (for exceptions see, Alt, et al., 2015, Ishimura & Sakurai, 2010, 2016; Ishimura, Tsukada, & Sakurai, 2013). A key consideration when working with three-dimentional motion capture is the choice of marker set (Milner, 2008). However, in studies that have used 3D motion capture, most fail to provide explicit information on the location of markers used (Alt et al., 2015; Ishimura & Sakurai, 2010, 2016; Ishimura, et al., 2013). Furthermore, there is a lack of published evidence regarding the reliability of such models in conditions representative of elite bend sprinting (i.e. radius, velocity and surface), since the majority of research focus on straight-line walking (e.g. Deschamps et al., 2012; Bishop, Paul & Thewlis, 2013; Milner & Brindle, 2016) or running (e.g. Ferber, McClay Davis, Williams, & Laughton, 2002; Alenezi, Herrington, Jones, & Jones, 2016; Milner & Brindle, 2016). However, bend sprinting occurs at a higher velocity (e.g. 9.86 m/s, Churchill, et al., 2015) than walking (e.g. 1.25 m/s, Milner & Brindle, 2016) or running (e.g. 3.65 m/s, Ferber, et al., 2002). These higher velocities produced during sprinting are likely to affect the reliability of a marker set, for example through an increase in skin movement artefact. Thus, it is not appropriate to assume the same reliability as for walking or running actions. Due to the issues highlighted, selecting a marker set for use in bend sprinting is problematic. Knowledge of reliability data enables researchers to determine the meaningfulness of reported differences between conditions and conclude with confidence that the effects are due to the independent variable and not the method of data collection or any other form of random variation (Hopkins, 2000). A standardised marker set with supporting reliability data would be a valuable tool for use in future bend sprinting research. It is important to examine both between- and within-day reliability. Whilst within-day reliability is affected by task execution, random error and skin movement artefact, additional factors such as system calibration and marker application may affect between-day measurements. Furthermore, calculation of minimal detectable difference (MDD) provide an indication of the magnitude of change required to be considered 'real' to aid researchers in the interpretation of results.

During kinematic analyses, the number of cameras and available laboratory space impact upon factors such as frame rate, resolution and desired capture volume. The resulting camera set-up can influence the coverage within the capture volume which will impact upon marker detection - for example areas of low coverage within the capture volume would likely increase marker drop-out rate. Furthermore, increasing the number of markers used has the consequence of increasing marker application and post-processing time (Vanrenterghem, Gormley, Robinson & Lees, 2010). In addition, there is potentially a decrease in the representativeness of the protocol through increased athlete interference with additional markers. It has been established that a lower limb and trunk marker set was sufficient for the accurate calculation of CoM location and associated variables (velocity, touchdown distance and turn of CoM) during bend sprinting (Judson, Churchill, Barnes, Stone & Wheat, 2017). For mean step velocity, touchdown distance and turn of CoM, ICC's in the range of 0.995-0.998 were reported showing excellent agreement between the simplified model and a whole-body marker set (Judson, et al., 2017). Since this reduced marker set has been shown to accurately represent full body movements it holds promise for use in future studies on bend sprinting, however, its reliability has yet to be established.

Therefore, the aim of this research was to determine the within- and between- day reliability of bend sprinting using 3D optoelectronic motion capture with a lower limb and trunk marker set. It was hypothesised that each measure would demonstrate excellent reliability, and within-day reliability would be greater in comparison to between-day.

Methods

Participants

Following ethical approval from Sheffield Hallam Research Ethics Committee, six sprinters (four males; mean age 20 ± 1 years; body mass 73.3 ± 3.0 kg; stature 1.79 ± 0.56 m and two females; mean age 22 ± 3 years; body mass 58.9 ± 1.4 kg; stature 1.66 ± 0.40 m) volunteered for this study. All athletes had experience of bend sprinting (200 and/or 400 m) and were active in training at the time of data collection. Mean personal best times were 22.76 ± 0.95 s (range 22.00 - 24.10 s; 200 m, four males) and 64.00 ± 0.00 s (400 m, two females). The study procedures were fully explained to participants who subsequently provided written informed consent.

Equipment

Kinematic data were collected using a 12-camera optoelectronic motion capture system (8 x Raptor model and 4 x Eagle model, Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 240 Hz. A right-handed lab coordinate system was defined using a rigid L-frame with four markers at known locations. The experimental set-up is demonstrated in Figure 1. Athletes ran primarily in the direction of the positive *y*-axis (anterior-posterior) in the capture volume, (see figure 1) where the positive *z*-axis was directed vertically upwards (longitudinal) and the positive *x*-axis was orthogonal to the other two axes (mediolateral, pointing to the athletes' right). A three-marker wand (length 500 mm) was used within the calibration volume to scale the individual camera views. The calibration volume (7 m long, 1.5 m wide and 2 m high) was located tangentially to the apex of the curve to record data through the 38 - 45 m section of the 60 m sprints.

*** Figure 1 near here ***

A modified Vicon Plug in Gait (PiG) marker set (lower limb and trunk; Judson et al., 2017) was used to model segments (torso, pelvis, thighs, shanks and feet, Figure 2). PiG has been used extensively in gait research (Kadaba, Ramakrishnan, & Wootten, 1990; Kulmala et al., 2017; Radzak, Putnam, Tamura, Hetzler, & Stickley, 2017). Although there are not yet any published data in sprinting, the unmodified PiG model is supported by reliability data during walking gait (Ferrari et al., 2008), revealing good reliability and correlation with other approaches including the Calibrated Anatomical System Technique (CAST; Benedetti, Catani & Leardini 1998). Retro-reflective, spherical markers (12.7 mm diameter) were placed on the following anatomical landmarks of the left and right leg: lateral malleolus, medial malleolus, shank (lower lateral 1/3), thigh (lower lateral 1/3 surface of the thigh), lateral femoral epicondyle, medial femoral epicondyle, greater trochanter, posterior superior iliac spine (left and right), anterior superior iliac spine (left and right), C7, T10, suprasternal notch, xiphoid process. Acromion process markers were included for the static trial only. The PiG model represents the foot as a single unit. However, this simplistic approach does not permit the measurement of movements within the foot such as metatarsophalangeal dorsi- and plantar-flexion which have been identified as important movements in sprinting (Bezodis, Salo, & Trewartha, 2012; Smith, et al. 2012). In addition, inversion and eversion may have importance during bend sprinting. Therefore, additional markers were placed on the posterior, medial and lateral calcaneus, 1st and 5th metatarsal bases, 1st, 2nd and 5th metatarsal heads and head of the 2nd toe (Smith, Lake, Lees, & Worsfold, 2012) (Figure 3). All foot markers were shoe mounted and thought to represent the movement of the underlying foot. The foot was modelled as three segments; rearfoot, forefoot and toebox (Figure 3).

Where possible, segments were defined according to ISB recommendations (Wu et al., 2002; Wu et al., 2005), with the exception of the multi-segment foot model which was defined in line with Cappozzo, Catani, Della Croce, and Leardini (1993).

*** Figure 2 near here ***

*** Figure 3 near here***

Test-retest protocol

Data were collected on a flat standard indoor track surface with a reconstructed bend replicating lane 1 (radius 36.5 m) of a standard 400 m running track (IAAF, 2008). Participants performed five trials at maximal effort for 60 m. Data collection started at 38 m where athletes were likely to be at maximum speed (Krzysztof & Mero, 2013). Approximately eight minutes were allowed between trials to allow full recovery and avoid the onset of fatigue (Churchill et al., 2015). Participants wore the same pair of their own sprint spikes for each testing session.

The test protocol was repeated two days to one week later, with the second session occurring at approximately the same time of day (i.e. morning or afternoon). The marker set was applied by the same researcher at each testing session.

Data processing

Cortex software (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA) was used to track and export raw 3D marker coordinate data. Automatic gap filling was performed using a cubic spline on all gaps <10 frames. Raw marker positions were filtered at 14-18 Hz using a low-pass, fourth order recursive Butterworth filter. Trunk, pelvis and thigh markers were filtered at 18 Hz, shank and ankle markers at 16 Hz and foot markers at 14 Hz. These cut-off frequencies were chosen using residual analysis with frequency range based upon previous sprint and multi-segment foot literature with a range of 7 - 20 Hz (Churchill et al., 2015; Hunter et al., 2004a, 2004b; Milner & Brindle, 2016; Queen, Gross, & Liu, 2006). Segments, local coordinate systems and joint centres were defined and constructed in Visual

3D software based on a static standing trial (version 6, C-Motion, Rockville, MD, USA). Body segment parameters were estimated from de Leva (1996) and adjusted to allow the addition of 0.2 kg to each foot which represents the mass of a spiked shoe (Hunter, Marshall, & McNair, 2004b).

Calculation of variables

Spatio-temporal and kinematic variables found to be of importance in previous bend sprinting research were selected for measurements and evaluation (Alt et al. 2015; Churchill et al., 2015). All variables were calculated separately for the left and right step. Left and right steps were defined by the foot that initiated the step.

Joint (orientation) angles were defined as the distal segment relative to the proximal segment, with the exception of the trunk that was defined relative to the lab coordinate system. The Cardan sequence *xyz* was used in line with ISB recommendations (Wu et al., 2002). Peak joint angles during the stance phase were calculated to enable standardisation of results with previous research (e.g. Alt et al., 2015). Values for the left limb in the transverse and frontal planes were multiplied by -1 for ease of interpretation. *Touchdown and take-off events* were defined using the fifth metatarsal head markers (MTH5). The mean plus two standard deviations of the vertical coordinates of the left and right MTH5 in the static trial were calculated and used as a threshold for ground contact in each participant. For each foot, touchdown was considered as the first data point where the vertical coordinate of the marker dropped below the defined threshold and vice-versa for take-off (Bezodis, Thomson, Gittoes & Kerwin, 2007). *Absolute speed* was calculated using the first central difference technique from the horizontal distance travelled in the anterior direction by the CoM. The mean of the instantaneous speeds was calculated from the first frame of ground contact to the last frame of the flight phase with the contralateral foot to give absolute speed over a step (Churchill et al., 2015). *Directional step length* was calculated using a vector between the horizontal positions of the 2^{nd} metatarsal head at consecutive ground contacts. A second vector was created between the horizontal positions of the CoM at consecutive ground contacts. The dot product of the two vectors gave directional step length (Churchill et al., 2015). *Step frequency* was calculated as absolute speed divided by directional step length. *Contact time* was the time from touchdown to take-off of the same leg and *flight time* the total step time (touchdown of one foot to touchdown of the contralateral foot) minus contact time. *Touchdown distance* (the horizontal displacement between the CoM and second metatarsophalangeal joint at touchdown) was calculated using an instantaneous progression vector for the CoM (calculated from the horizontal position of the CoM one frame before the instant of interest to the horizontal position of the CoM one frame after the instant of interest, then divided by its norm to create a unit vector). A horizontal vector from the CoM to the 2nd metatarsal head of the touchdown limb was also calculated. The dot product of the horizontal vector onto the instantaneous progression vector gave touchdown distance (Churchill et al., 2015).

Reliability measures

The reliability of the marker set was established using intraclass correlation coefficient (ICC) tests. ICCs for absolute agreement were used to determine the reliability between sessions (ICC (3,*k*) - where *k* is equal to the number of trials (five)). Within-day reliability was determined using ICC (3,1) and calculated for all trials on the first day of testing. ICCs were interpreted according to Cicchetti (1994), where <0.40 represents *poor* agreement; 0.40 to 0.59 *fair* agreement; 0.60 to 0.75 *good* agreement and > 0.75 *excellent* agreement. In accordance with recommendations from Koo and Li (2016), 95% confidence intervals (CI) were also presented and Cicchetti's (1994) descriptors were applied to the interpretation of CIs. As recommended by Koo and Li (2016), for a variable to be considered as having 'excellent' reliability, both upper and lower bounds must fall within the excellent range (i.e. > 0.75).

Standard error of measurement (SEM) was calculated from between-day data using the formula (Weir, 2005):

$$\text{Standard deviation of the mean difference (SD) x } \sqrt{1 - ICC} \qquad (1)$$

Minimal detectable difference (MDD) was calculated from between-day data using the formula (Weir, 2005):

$$1.96 \text{ x SEM x } \sqrt{2} \qquad (2)$$

Results

For between-day reliability (ICC 3, *k*), analysis of 95% CI revealed all but two spatio-temporal variables (Table 1, Table 2) were fair to excellent (0.419- 1.000). Right touchdown distance and left step length were poor to excellent (0.180 - 0.980). For all variables, within-day reliability (ICC 3, 1: 0.258 - 1.000) was greater than between-day reliability (ICC 3, *k*: 0.180 - 0.975). Right step frequency displayed a between-day MDD of 0.16 Hz, whereas right and left contact time had a between-day MDD of 0.02 s. Contact time also demonstrated a small between-day SEM (0.006-0.007 s). Within-day SEM and MDD were smaller when compared to between-day values.

For joint kinematics (Table 3, Table 4), 29 of 44 variables demonstrated excellent between-day reliability when analysing the 95% CI (0.780-0.999). Six frontal and transverse plane variables (left knee internal rotation, right hip external rotation, right knee abduction, right knee adduction, right knee external rotation, right ankle external rotation) demonstrated poor to excellent reliability (0.075 - 0.985). Within-day reliability (ICC 3, 1: 0.228-0.999) was greater than between-day variability (ICC 3, *k*, 0.075 - 0.999) for the majority of joint kinematic variables. MDD ranged from 1-11° across all variables. Between-day SEM values were < 4° across all conditions, however within-day SEM and MDD were smaller.

*** Table one near here ***

*** Table two near here ***

*** Table three near here ***

*** Table four near here ***

Discussion and Implications

The purpose of this study was to determine the between- and within-day reliability of a lower limb and trunk marker set during maximal velocity bend sprinting. All athletes were experienced bend sprinters and mean absolute speed was similar between days. All variables (both spatio-temporal and kinematic) demonstrated excellent within-day reliability. Data from this study demonstrated consistently poorer between-day reliability than within-day reliability. When compared to between-day reliability, greater within-day reliability has been a common finding throughout previous reliability investigations involving running (Ferber et al., 2002; Alenezi, et al., 2016). Between-day reliability for kinematic variables during walking and running has been reported with ICC's (without 95% CI's) in the range of 0.51-0.72 (Alenezi, et al., 2016); 0.54-0.93 (Ferber, et al., 2002) and 0.644 - 0.993 (Milner & Brindle, 2016). In comparison to between-day reliability, within-day reliability for kinematic variables is typically greater: 0.63-0.94 (Alenezi, et al., 2016); 0.92-0.99 (Ferber, et al., 2002) and 0.881 - 0.994 (Milner & Brindle, 2016). Therefore, the between- (0.739 - 0.989) and within-day (0.761-0.995) reliability demonstrated for joint kinematics within the present study are comparable to previous research in walking and running. Greater within-day reliability suggests that, where possible, data for each individual athlete should be collected during a single session. Should this not be appropriate, the between-day MDD's provide an indication of the margin for error that should be applied when interpreting results.

SEM and MDD provide an indication of the magnitude of change required in experimental studies to be confident that a real change has occurred. The present findings demonstrated a MDD of 2° (left step) and 1° (right step) for peak hip adduction angles comparing favourably to the MDD of 6.90° during running and 8.37° in cutting previously reported (Alenzi et al., 2016). It is likely these differences can be attributed to the inclusion of recreational athletes by Alenezi et al. (2016) in comparison to the present study where athletes were trained and experienced in the execution of a specific task. Moreover, the cutting task used by Alenezi et al. (2016) may also contribute to these differences since it may be difficult for non-expert participants to replicate the movement consistently. In addition, Alenezi et al. (2016) found knee internal rotation angle during the cutting manoeuvre (which due to its lateral change of direction shares some similarities with bend sprinting) demonstrated the lowest between-day ICC (0.40) with an MDD of 11.3°. This is similar to the current findings, where one of the lowest between-day ICC was left knee internal rotation angle (0.782) with a MDD of 7°. Whilst this is larger than the 5° difference in left knee internal rotation angle reported by Alt et al., (2015), the reliability can be increased by collecting data on the same day. Doing so would decrease the required MDD from 7° to 3°, thus making the protocol sensitive to smaller changes such as those reported by Alt et al., (2015).

Touchdown distance and left step length in this study failed to achieve excellent between-day reliability, supporting previous findings that touchdown distance was one of the least reliable variables examined during straight line sprinting (Hunter, Marshall, and McNair 2004a). In addition, Standing and Maulder (2017) reported between-day ICCs of 0.65 and 0.44 for step length during the first and third steps of the acceleration phase. However, Hunter, Marshall and McNair (2004a) showed that reliability increased for all variables when averaging across three trials, suggesting a single trial is insufficient to capture the natural variance within an athlete's technique. Therefore, as also demonstrated by the results of average measures ICC(3, *k*) here, future research should use an average of multiple trials to improve reliability of variables such as step length and touchdown distance. Step length results of the present study demonstrate excellent within-day reliability for both steps, however high standard deviations were reported, suggesting step length is variable both between participants (SD: 0.08 - 0.11 m) and between-days (ICC 3, *k*: 0.184 - 0.991). These variations in step length might contribute towards the different results found between previous bend sprinting studies. For example, Churchill et al. (2015; 2016) suggested a reduction in right step length is present on the bend, while Alt et al. (2015), found neither left or right step length was affected during bend sprinting. However, this may have been a result of the differing protocols used, since Alt et al. (2015) measured sub-maximal velocity compared to Churchill et al., (2015; 2016) who evaluated maximal velocity. Here, results provide increased clarity for future research on what constitutes a real change in step length. The ICCs for the remaining spatio-temporal variables represented excellent agreement for both between- and within-day reliability, with small (e.g. contact time 0.006 - 0.007 s) SEM reported throughout. Notwithstanding the poor and fair 95% CI reported for some ICC's, the resulting MDD is low enough to detect changes in spatio-temporal variables between conditions. For example, a 0.08 m MDD has been established for right step length. Churchill et al. (2015) reported a decrease of 0.10 m in right step length on the bend compared to the straight. In addition, Ishimura & Sakurai (2016) reported a difference of 0.14 m between right and left step length on the bend. Therefore, the marker set is reliable for future use with spatio-temporal variables.

Reliability of sagittal plane variables was generally greater than variables calculated in the frontal and transverse planes replicating common findings of reliability analyses. For example, a review of reliability in kinematic measures of walking gait demonstrated the lowest reliability and highest error occurred most frequently in the transverse plane (McGinnley, Baker, Wolfe & Morris, 2009). In addition, the values reported here are consistent with previous reliability investigations of multi-segment foot models during walking (Bishop, Paul, & Thewlis, 2013; Deschamps et al., 2012) and running (Milner & Brindle, 2016). Moreover, comparison of the MDD's with previous bend sprinting literature suggests the protocol is sensitive enough to detect the magnitude of change previously reported. For example, Alt et al. (2015) and Churchill et al. (2015) have reported an increase in left hip adduction on the bend compared to the straight of 6° and 8° respectively. The present study established a MDD of 1° and 2° for within- and between-day protocols. In addition, although right ankle external rotation demonstrated poor to excellent between-day reliability, the associated MDD is 4°, which is smaller than the 5° difference between left and right foot on the bend reported by Alt et al. (2015). In addition, right ankle external rotation MDD can be decreased further to 2° by collecting data on the same day. Therefore, the marker set can reliably be used in future research.

A radius replicating lane one (36.5 m) was used in this study. Whilst this may be most useful from a research perspective since technical adaptations have been shown to be more prominent in lanes with a smaller radius (Churchill, Trewartha, & Salo, 2018), athletes tend to avoid training in this lane, which may have contributed towards variance between days.

Conclusion

The reliability of a lower limb and trunk marker set with a multi-segment foot has been established for bend sprinting. The results presented partially support the hypothesis. Overall, between-day ICCs were fair to excellent for all variables and comparable to those previously reported during straight-line walking and running gait. Within-day reliability was greater than between-day reliability, suggesting that, where possible, data collection for a single athlete should take place on the same day. The between-day data presented takes into account variance in athlete technique alongside the reliability of the equipment set-up, calibration, random error and marker placement. As such, this will inform protocol design and the determination of meaningful differences between conditions in future kinematic studies of bend sprinting. The lower limb and trunk marker set is a reliable model to use in future analyses of bend sprinting. However, results should be interpreted with the reported MDD's in mind.

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Table 1: Left step spatio-temporal variables. ICC (3, 1) represents within-day reliability and ICC (3, k) between-day reliability. 95% lower- (LB) and upperbound (UB) confidence intervals are presented. Variables showing less than excellent (<0.75) reliability are highlighted with an asterisk (*). ± indicates the standard deviation of the group mean.

Variable	**Left**		**ICC (3, 1)**	**95% LB**	**95% UB**	**SEM**	**MDD**	**ICC (3, *k*)**	**95% LB**	**95% UB**	**SEM**	**MDD**
	Day One	***Day Two***										
Absolute speed (m/s)	7.89 ± 0.75	8.01 ± 0.67	0.990	0.964	0.999	0.02	0.04	0.985	0.946	0.989	0.03	0.08
Directional step length (m)	1.94 ± 0.08	2.00 ± 0.08	0.832	0.315*	0.995	0.03	0.08	0.738*	0.184*	0.980	0.04	0.10
Contact time (s)	0.128 ± 0.01	0.127 ± 0.01	0.949	0.748	0.994	<0.01	0.01	0.815	0.419*	0.933	0.007	0.02
Flight time (s)	0.122 ± 0.03	0.126 ± 0.02	0.857	0.456*	0.983	<0.01	0.01	0.796	0.536*	0.911	0.01	0.03
Step frequency (Hz)	4.07 ± 0.32	4.01 ± 0.26	0.981	0.898	1.000	0.03	0.07	0.975	0.834	1.000	0.03	0.08
Touchdown distance (m)	0.40 ± 0.08	0.42 ± 0.08	0.791	0.258*	1.000	0.02	0.06	0.701*	0.436*	0.855	0.02	0.07

Table 2: Right step spatio-temporal variables. ICC (3, 1) represents within-day reliability and ICC (3, k) between-day reliability. 95% lower- (LB) and upperbound (UB) confidence intervals are presented. Variables showing less than excellent (<0.75) reliability are highlighted with an asterisk (*). ± indicates the standard deviation of the group mean.

Variable	**Right**		**ICC (3,1)**	**95% LB**	**95% UB**	**SEM**	**MDD**	**ICC (3, *k*)**	**95% LB**	**95% UB**	**SEM**	**MDD**
	Day One	***Day Two***										
Absolute speed (m/s)	7.87 ± 0.78	8.01 ± 0.67	0.973	0.908	0.997	0.02	0.04	0.984	0.944	0.999	0.03	0.08
Directional step length (m)	1.93 ± 0.11	2.00 ± 0.11	0.939	0.782	0.993	0.03	0.08	0.924	0.768	0.991	0.03	0.09
Contact time (s)	0.108 ± 0.01	0.108 ± 0.01	0.963	0.826	0.996	<0.01	<0.01	0.878	0.734	0.944	0.006	0.02
Flight time (s)	0.119 ± 0.03	0.113 ± 0.05	0.935	0.693	0.995	0.003	0.01	0.761	0.420*	0.897	0.006	0.02
Step frequency (Hz)	4.09 ± 0.33	4.02 ± 0.27	0.949	0.818	0.994	0.06	0.16	0.958	0.869	0.995	0.06	0.16
Touchdown distance (m)	0.34 ± 0.07	0.38 ± 0.07	0.982	0.867	0.997	<0.01	<0.01	0.684*	0.180*	0.874	0.03	0.08

Table 3: Left step joint kinematics. ICC (3, 1) represents within-day reliability and ICC (3, k) between-day reliability. 95% lower- (LB) and upperbound (UB) confidence intervals are presented. Variables showing less than excellent (<0.75) reliability are highlighted with an asterisk (*). ± indicates the standard deviation of the group mean.

Peak joint angle during stance (°)	**Left**		**ICC**	**95%**	**95%**	**SEM**	**MDD**	**ICC**	**95%**	**95%**	**SEM**	**MDD**
	Day One	***Day Two***	(3, 1)	LB	UB			(3, *k*)	LB	UB		
Hip Flexion	42 ± 8	38 ± 16	0.926	0.763	0.988	1.92	5	0.930	0.782	0.992	2.55	7
Hip Extension	-15 ± 5	-14 ± 11	0.975	0.922	0.996	0.84	2	0.917	0.738	0.990	2.36	7
Hip Abduction	-5 ± 3	-5 ± 4	0.946	0.825	0.991	0.69	2	0.941	0.714	0.999	0.87	2
Hip Adduction	9 ± 4	8 ± 5	0.988	0.960	0.998	0.24	1	0.956	0.845	0.997	0.58	2
Hip Internal Rotation	-2 ± 9	-2 ± 8	0.992	0.973	0.999	0.26	1	0.989	0.965	0.999	0.42	1
Hip External Rotation	-16 ± 8	-14 ± 7	0.963	0.861	0.996	0.55	2	0.967	0.897	0.996	0.72	2
Knee Flexion	-40 ± 5	-42 ± 9	0.952	0.803	0.997	0.81	2	0.967	0.882	0.998	0.87	2
Knee Extension	-18 ± 7	-18 ± 7	0.975	0.911	0.997	0.70	1	0.978	0.932	0.997	0.54	1
Knee Abduction	-3 ± 3	-2 ± 4	0.969	0.890	0.996	0.57	2	0.936	0.780	0.995	1.33	4
Knee Adduction	4 ± 4	3 ± 3	0.942	0.815	0.991	0.38	1	0.937	0.808	0.992	0.40	1
Knee Internal Rotation	7 ± 7	8 ± 10	0.947	0.814	0.994	1.18	3	0.782	0.190*	0.985	2.39	7
Knee External Rotation	-13 ± 9	-9 ± 10	0.956	0.862	0.993	1.55	4	0.933	0.794	0.992	2.05	6
Ankle Dorsiflexion	107 ± 6	108 ± 9	0.962	0.865	0.996	0.96	3	0.934	0.795	0.992	2.37	7
Ankle Plantarflexion	63 ± 12	58 ± 10	0.960	0.850	0.995	1.94	5	0.932	0.786	0.992	3.87	11
Ankle Eversion	-10 ± 13	-12 ± 13	0.994	0.979	0.999	0.32	1	0.971	0.909	0.996	1.06	3
Ankle Inversion	5 ± 14	6 ± 11	0.992	0.972	0.999	0.49	1	0.970	0.907	0.996	1.85	5
Ankle Internal Rotation	24 ± 6	22 ± 6	0.949	0.819	0.994	0.66	2	0.852	0.549*	0.982	2.31	6
Ankle External Rotation	3 ± 5	4 ± 3	0.976	0.910	0.997	0.69	2	0.871	0.590	0.985	1.76	5
Midfoot Inversion	0 ± 4	0 ± 3	0.962	0.860	0.996	0.53	1	0.872	0.595*	0.985	1.64	5
Midfoot Eversion	7 ± 5	7 ± 1	0.985	0.948	0.998	0.34	1	0.877	0.603*	0.986	1.88	5
MTP Dorsiflexion	36 ± 8	38 ± 6	0.995	0.980	0.999	0.38	1	0.914	0.729*	0.990	2.21	6
MTP Plantarflexion	13 ± 5	13 ± 6	0.906	0.648*	0.989	0.97	3	0.840	0.504*	0.981	2.20	6

Table 4: Right step joint kinematics. ICC (3, 1) represents within-day reliability and ICC (3, k) between-day reliability. 95% lower- (LB) and upperbound (UB) confidence intervals are presented. Variables showing less than excellent (<0.75) reliability are highlighted with an asterisk (*). ± indicates the standard deviation of the group mean.

Peak joint angle during stance (°)	**Right**		**ICC** (3,1)	**95%** LB	**95%** UB	**SEM**	**MDD**	**ICC** (3, *k*)	**95%** LB	**95%** UB	**SEM**	**MDD**
	Day One	***Day Two***										
Hip Flexion	39 ± 10	43 ± 11	0.909	0.714	0.985	1.81	5	0.883	0.580	0.992	3.15	9
Hip Extension	-15 ± 8	-14 ± 15	0.989	0.962	0.999	0.40	1	0.961	0.861	0.997	1.70	5
Hip Abduction	-7 ± 4	-6 ± 4	0.963	0.871	0.996	0.46	1	0.966	0.896	0.996	0.46	1
Hip Adduction	4 ± 6	6 ± 5	0.985	0.945	0.998	0.40	1	0.976	0.927	0.997	0.41	1
Hip Internal Rotation	3 ± 5	4 ± 8	0.923	0.733*	0.991	1.36	4	0.907	0.705*	0.989	1.46	4
Hip External Rotation	-9 ± 2	-9 ± 5	0.761	0.228*	0.962	2.41	7	0.752	0.200*	0.971	2.24	6
Knee Flexion	-44 ± 5	-42 ± 7	0.860	0.461*	0.984	2.21	5	0.831	0.479*	0.980	1.90	5
Knee Extension	-18 ± 7	-16 ± 8	0.951	0.822	0.994	0.70	1	0.972	0.913	0.997	0.42	1
Knee Abduction	-3 ± 2	- 4 ± 3	0.891	0.613*	0.987	0.88	2	0.778	0.308*	0.959	0.55	2
Knee Adduction	2 ± 1	3 ±4	0.855	0.320*	0.978	0.87	2	0.809	0.493*	0.990	1.23	3
Knee Internal Rotation	1 ± 8	-2 ± 9	0.961	0.862	0.995	1.01	3	0.973	0.886	0.999	1.09	3
Knee External Rotation	-14 ± 4	-13 ± 9	0.807	0.327*	0.997	1.64	5	0.739*	0.075*	0.982	3.67	10
Ankle Dorsiflexion	98 ± 6	97 ± 8	0.954	0.854	0.993	1.25	3	0.940	0.814	0.993	1.10	3
Ankle Plantarflexion	52 ± 13	51 ± 13	0.944	0.804	0.993	1.52	4	0.961	0.864	0.997	1.37	4
Ankle Eversion	-4 ± 8	-4 ± 7	0.988	0.956	0.999	0.60	2	0.897	0.705*	0.983	2.68	6
Ankle Inversion	12 ± 4	12 ± 9	0.961	0.874	0.994	1.38	4	0.816	0.294	0.987	3.33	9
Ankle Internal Rotation	-7 ± 4	- 6 ± 6	0.948	0.815	0.994	1.06	3	0.922	0.734	0.994	1.25	3
Ankle External Rotation	-17 ± 3	- 16 ± 2	0.929	0.708	0.995	0.75	2	0.793	0.353*	0.976	1.34	4
Midfoot Inversion	-9 ± 5	-6 ± 4	0.937	0.799	0.990	0.92	3	0.827	0.510*	0.978	2.84	8
Midfoot Eversion	-3 ± 4	0 ± 3	0.960	0.887	0.996	0.77	2	0.880	0.639*	0.986	1.66	5
MTP Dorsiflexion	36 ± 6	36 ± 5	0.918	0.703	0.990	1.18	3	0.914	0.785	0.994	1.91	5
MTP Plantarflexion	12 ± 5	10 ± 4	0.945	0.804	0.994	1.53	4	0.908	0.839	0.989	1.77	5

Figure 1: Plan view of test set-up (not to scale).

Figure 2: Lower limb and trunk marker set anatomical marker locations

Figure 3: Multi-segment foot model marker placement and segment division. The solid line (-) represents the forefoot defined by the first and fifth metatarsal base and first, second and fifth metatarsal head. Dashed line (- - -) represents the toebox defined by first, second and fifth metatarsal heads and the head of the second toe. Circular line (…) represents the rearfoot segment defined by posterior, lateral and medial calcaneus and a virtual intermedius calcaneus marker.