The inter-laboratory equivalence for lower limb kinematics and kinetics during unplanned sidestepping.

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Abstract (Word count 198 of 250)

Much inter-intra-tester kinematic and kinetic repeatability research exists, with a paucity of literature investigating their inter-laboratory equivalence. The objective of this research was to evaluate the inter-laboratory equivalence between time varying unplanned sidestepping (UnSS) lower limb kinematics and kinetics. Eight elite female athletes completed an established UnSS procedure at two different motion capture laboratories (UK and Australia). Three dimensional time varying unplanned sidestepping joint kinematics and moments were compared. Discrete variables were change of direction angles and velocity. Waveform data were compared using mean differences, 1D 95% Confidence Intervals (CI) and RMSE. Discrete variables were compared using 0D 95% CI. The mean differences and 95% CI for UnSS kinematics broadly supported equivalence between laboratories (RMSE≤5.1°). Excluding hip flexion/extension moments (RMSE=1.04Nm/kg), equivalence was also supported for time varying joint moments between laboratories (RMSE≤0.40Nm/kg). Dependent variables used to characterise UnSS were also equivalent. When consistent experimental and modelling procedures are employed, consistent time varying UnSS joint kinematic and moment estimates between laboratories can be obtained. We therefore interpret these results as support of equivalence, yet highlight the challenges of establishing between-laboratory experiments or data sharing, as well as establishing appropriate ranges of acceptable uncertainty. These findings are important for data sharing and multi-centre trials.

Key Words: consistency; injury; screening; SPM; knee; ACL

Introduction

For over 20 years, there has been a growing body of multidisciplinary research focused on understanding the principles and mechanisms underpinning effective non-contact anterior cruciate ligament (ACL) injury prevention (Hewett at al., 1996; Donnelly et al., 2012a). This is in part attributed to the large socioeconomic burden(s) ACL injuries place on our global society. For example, ACL injury management, which is commonly met with expensive surgical interventions and lengthy rehabilitation periods (4-14 months) places an annual multi-billion dollar burden upon health agencies globally (Donnelly et al., 2012a; Hartigan et al., 2010). The health impact(s) on the injured athlete are also considerable as they are tied to high rates of re-injury during and following rehabilitation (Orchard et al., 2001). In addition, ACL injured athletes are predisposed to a twofold increase in risk of developing debilitating knee osteoarthritis later in life (~10 years) (Oiestad et al., 2009).

Given that the vast majority of non-contact ACL injuries occur during sidestepping and single-leg landing tasks (Cochrane et al., 2007; Koga et al., 2010; Krosshaug et al., 2007), they are thought to be preventable. Therein, motion capture laboratories world-wide have developed innovative experimental testing procedures designed to mimic the internal and external forces associated with non-contact ACL injury events in attempts to understand the mechanical factors underpinning these injuries (Donnelly et al. 2012a; Markolf et al., 1995). In general, these testing procedures use single/double support landing (Hewett et al., 1996; Blackburn et al., 2008; Kipp et al., 2011; McLean et al., 2010) or planned/unplanned sidestepping (Besier et al., 2001; Dempsey et al., 2014; Donnelly et al., 2012b, 2012c, 2017). Clinically relevant kinematic, kinetic and muscle activation measures are then calculated to characterise an athlete's risk of ACL injury/re-injury (Donnelly et al., 2012a). Though considered a valid research approach, little investigation has been conducted testing the consistency of these experimental procedures between independent motion capture laboratories. This places practical limitations on the shared use of motion data for *'Big Data'* type research (i.e., AI, DNN, machine learning) (Johnson et al., 2018), exploratory mechanistic research (Morgan et al., 2014; Donnelly et al., 2012c) and/or the ability to perform large sample, adequately powered, multi-centre, prospective intervention trials (Caraffa et al., 1996; Hewett et al., 1999; Myklebust et al., 2003).

Research by DiCesare et al. (2015) has shown the three-dimensional (3D) lower limb kinematic and kinetic repeatability of a single-leg cross drop landing task between testing centres presented with moderate to strong repeatability (CMC = 0.647 – 0.956) (Cohen 1988). These results show in principle that motion data of a single-leg cross drop task performed from a fixed height are comparable between laboratories. Though a repeatable within laboratory experimental design (Donnelly et al., 2012b; Mok et al., 2017; Sankey et al., 2015), it is unknown if a participant's lower limb time varying kinematic and kinetic waveforms would differ between laboratories if more complex testing protocols, like unplanned sidestepping were performed.

The primary purpose of this research was to determine if an athletes' three-dimensional (3D) time varying lower limb joint kinematics and moments during the stance phase of unplanned sidestepping would be equivalent if the same athletes were assessed between two independent motion capture laboratories. The second purpose of this research was to determine if the zero dimensional (0D) variables commonly used to characterise an unplanned sidestepping task (i.e., change of direction angle, velocity and contact time) would be consistent between motion capture laboratories.

It is hypothesised equivalence in 3D, time varying lower limb joint kinematics and joint moments through the stance phase of unplanned sidestepping between motion capture laboratories will be observed. It is further hypothesised there will be equivalence between the 0D dependent variables used to characterise an unplanned sidestepping task between motion capture laboratories.

Methods

The participants in this study were the Australian Women's National Field Hockey team. Their competing in the Glasgow 2014 Commonwealth games provided a unique opportunity to test these athletes across continents. One test session was conducted at the University of Western Australia (UWA) in either November, 2013 or August, 2014, and a second session at Liverpool John Moores University (LJMU) in July, 2014. Sixteen athletes deemed fit and healthy by the team's medical staff were eligible to take part in this study. Whilst we initially expected a drop-out rate of around 20% only eight participants (1.68 ± 0.10m, 64.0 ± 9.2 kg) were able to complete both testing sessions were due to de-selection, injury or availability. All participants provided informed consent prior to experimental data collections, which were approved by the Human Research Ethics Committees at The University of Western Australia (UWA) (RA/4/1/5333) and Liverpool John Moores University (LJMU) (12/SPS/022).

For both testing sessions, the same experimental laboratory procedures and kinematic & inverse dynamic modelling protocols were performed (Besier et al., 2001, 2003; Robinson & Vanrenterghem 2012). In addition, all athletes wore their normal training attire and their team sponsored shoe wear (ASICS women's gel-Kayno 21, Kogan, Australia Pty Ltd.). First, the electronic signalling system used to instruct athletes which sporting tasks (i.e., straight-line run, cross-over cut or sidestepping task) and anticipatory condition (i.e., planned vs unplanned) to perform during testing were mapped between testing centres (Donnelly et al., 2012b). Second, the same tester applied a standardised Calibrated Anatomical Systems Technique (CAST) kinematic marker set to all participants during each testing session (Cappozzo et al., 1995; Besier et al, 2001; Donnelly et al., 2012b). Interested readers can see a full description of the marker set within the supplementary materials section (Figure S1). Third, the same, kinematic model, functional model calibration and dynamic testing procedures were performed in each lab (Besier et al., 2003; Donnelly et al., 2012b; Robinson & Vanrenterghem 2012). For the participant-specific kinematic model calibration trials, functional hip joint centre and knee axes protocols were performed (Besier et al., 2001). For the successful completion/inclusion of the dynamic running and change of direction trials, in-laboratory approach velocities were restricted to a range of 4.5 m/s and 5.5 m/s, and change of direction angles to 45°. These experimental parameters were chosen as they have been shown previously to be repeatable in a test- retest context (Donnelly et al., 2012b) (Figure 1).

<<Insert Figure 1 Here>>

For the UWA testing site, kinematic marker data were recorded using a hybrid 22-camera Vicon MX/T40 system (Oxford Metrics, Oxford, UK) operating at 250Hz (minimum residuals during laboratory calibration was <0.4mm) and ground reaction forces (GRF) with a 1.2 x1.2m AMTI force plate (AMTI, Watertown, MA) operating at 2,000Hz. For the LJMU testing site, kinematic marker data were recorded using a 10-camera Qualisys system (Gothenburg, Sweden) operating at 250Hz (minimum residuals during laboratory calibration was <0.4) and GRFs with a 0.9 x 0.6m Kistler force plate (Kistler, Winterthur, Switzerland) operating at 2,000Hz. Only unplanned sidestepping trials were used for analysis. Kinematic data were labelled and low pass filtered at 14 Hz with a 4th order dual pass Butterworth filter in Nexus 2.0 (Oxford Metrics, Oxford, UK) for the UWA site and labelled in QTM (Qualisys, Gothenburg, Sweden) and filtered with the same characteristics in Visual3D (v. 6.00.16, C-Motion, Kingston, Canada) for the LJMU site. The stance phase of sidestepping was defined as when the vertical GRF vector was >10N.

All motion capture data from both testing sites were imported into Visual3D (v. 6.00.16, C-Motion, Kingston, Canada) for kinematic and kinetic modelling. Inspect 3D (C-Motion, Kingston, Canada) was used for follow-on quality control analysis. Functional hip joint centres and knee axes were calculated in Visual3D as per Robinson & Vanrenterghem (2012). Following ISB recommendations (Wu et al., 2002); the 3D lower limb kinematics of each participant's self-selected preferred stance limb were calculated. Inverse dynamics was used to calculate externally applied joint moments (Robinson & Vanrenterghem 2012). Time varying flexion/extension, ab/adduction and int/external rotation hip and knee joint kinematics and joint moments, as well as ankle plantar/dorsi flexion joint kinematics and joint moments were all calculated during stance. The time varying (one-dimensional; 1D) kinematic and kinetic waveforms were time normalised to 100% of stance, and joint moments were amplitude normalised to body mass (kg). The discrete variables used to characterise the unplanned sidestepping task were whole body centre of mass change of direction angles, velocity at 0% and 100% stance as well as stance limb contact time from 0 through 100% of stance (Vanrenterghem et al., 2012).

The time varying (1D) joint kinematic and joint moment data between motion capture laboratories were compared for equivalence by calculating the systematic bias using the open-source SPM1D Python package (Pataky, 2012) in Anaconda Navigator 1.9.12. Specifically, to determine equivalence, the mean of the paired differences and 1D 95% confidence intervals for a paired design were calculated (Pataky et al. 2015, Atkinson & Nevill, 2007) ($\alpha = 0.05$). Independently, root mean squared error (RMSE) estimates between kinematic waveforms were also calculated. The mean of the paired differences and 95% confidence intervals were also calculated for the 0D task- related variables following a paired samples t-test ($\alpha = 0.05$).

Results

The 1D confidence intervals encapsulated zero for all 3D lower limb kinematics collected at the UWA and LJMU motion capture laboratories (Figure 2). The RMSE for the hip, knee and ankle kinematics, between test sites were all <5.1°.

<<Insert Figure 2 Here>>

Excluding hip flexion/extension moments, all 1D confidence intervals encapsulated zero for all joint moment estimates collected between the UWA and LJMU motion capture laboratories

(Figure 3). For the time varying hip flexion/extension moment, the confidence interval was outside zero for 7-46% of stance. The RMSE differences of all degrees of freedom apart from hip flexion/extension (1.04Nm/kg) joint moments between motion capture laboratories were ≤0.40Nm/kg.

<<Insert Figure 3 Here>>

The 0D confidence intervals encapsulated zero for all dependent variables used to characterise an unplanned sidestep between motion capture laboratories. Mean differences in change of direction angles, velocity at 0% stance, velocity at 100% stance and stance limb contact through 100% stance were 5°, 0.0 m/s, 0.1 m/s and 0.02 seconds respectively (Table 1).

<<Insert Table 1 Here>>

Discussion

In general, results broadly confirmed our primary hypotheses; lower limb time varying unplanned sidestepping joint kinematics, joint moments and dependent variables characterising an unplanned sidestep were equivalent between motion capture laboratories. Equivalence was determined using 95% CI to interpret the systematic bias between laboratories. Further scrutiny of these confidence intervals shows that there are varying degrees of uncertainty across kinematic and kinetic measures within which the true systematic difference exists. It is probably most appropriate to consider the time-varying uncertainty across multiple planes and joints somewhat holistically. Whilst equivalence overall was demonstrated, recruiting additional participants would have reduce the uncertainty of the true systematic differences (Atkinson & Nevill, 2007). We therefore interpret these results as broadly in support of equivalence yet highlight the challenge of establishing between-laboratory experiments or data sharing and establishing appropriate ranges within which acceptable uncertainty and participant numbers exists. Sport scientists should then be cautiously optimistic of establishing equivalence when comparing and sharing time-varying kinematic and kinetic data even when established, well documented experimental testing procedures and modelling protocols are used.

Our RMSE joint kinematic measurement uncertainty (<5.2°) aligns with previous between session sidestepping repeatability research, which have reported within and between session typical errors between 1.1 and 5.6° (Mok et al., 2017). Our average joint moments errors during unplanned sidestepping gait (0.22Nm/kg) are in close alignment with the measurement uncertainty of individuals during walking gait (~0.10Nm/kg). The degree of freedom with the largest measurement uncertainty was hip flexion/extension (≤0.40Nm/kg), which again aligns with previous repeatability research (i.e., between session sidestepping typical errors are 0.54Nm/kg) (Mok et al., 2017). This may be in part due to the differences in running surfaces between laboratories; the UWA running surface was fit with artificial grass turf surface and the LJMU was fit with a rubber Mondo surface (Figure 1). This likely would have altered the surface's frictional force characteristics as well as the anterior posterior, medial lateral and free moment reaction forces applied to each athlete's stance limb during the weight acceptance phase of unplanned sidestepping. With it known participants wore the same footwear, and it presumed that the rubber surface possessed a higher coefficient of friction than the grass turf; it is plausible the larger peak internal rotation moments observed by athletes' tested at the LJMU motion capture laboratory were due, in part to differences in the flooring surfaces' co-efficient of friction. As the coefficient of friction between testing centres was not measured, the plausible mechanical relationship between a laboratory floors' co-efficient of friction and peak internal rotation knee moments during the weight acceptance phase of unplanned sidestepping remains to be verified by future research.

With the field of biomechanics moving towards '*Big Data*' and mechanistic exploratory type research, these results, in principle show that we have the ability to build large, cloud based data repositories to start answering artificial intelligence, and cause-effect (*'what if'*) type research questions within the ACL field. These findings, along with previous research (DiCesare et al., 2015) provide foundational evidence that multi-centre clinical and prospective intervention trials are indeed practical and plausible once appropriate equivalence is established. This is an important finding for researchers attempting to link large volume, heterogeneous prospective injury data to the underlying mechanical variables characteristic of sidestepping and single-leg landing sporting tasks. Once these mechanical variables are correctly mapped, researchers will be better able to design effective, robust and repeatable community based ACL injury prevention and rehabilitation training protocols that target the factors related to ACL injury/re-injury risk and events. From here we will hopefully observe reductions, instead of increases in world-wide ACL injury rates (Donnelly et al., 2012a), lessening the socioeconomic burden of these injuries on health care systems globally.

As with all research studies, it was met with some limitations. First, the final sample size was lower than expected with eight athletes completing testing sessions at both the UWA (Australia) and LJMU (UK) motion capture laboratories. This meant that the 1D confidence intervals were wider than we would have preferred. It should be noted however consistency was observed even though some uncertainty existed around the true between-laboratory bias. Second, this study was conducted on a sample of elite female athletes whose motor patterns may be more automated in comparison to adolescent or sub-elite populations. Future research is recommended to assess the kinematic and kinetic measurement consistency of unplanned sidestepping testing protocols among heterogeneous groups of team sport athletes. Lastly, the surfaces of the UWA (thin artificial grass turf) and LJMU (thin rubber Mondo surface) were different. These differences in flooring may in part explain why there were time varying differences in hip joint flexion/extension moments, however this is only speculation, which requires future research to verify. Interestingly, previous research has also identified the hip flexion/extension degree of freedom as possessing the largest measurement uncertainty (i.e., between and within tester typical errors; 0.30Nm/kg and 0.54Nm/kg) when compared with all other lower limb degrees of freedom (Mok et al., 2017). Together these results suggest the modelling of the hip joint centre during dynamic sporting tasks may require additional attention within the musculoskeletal modelling literature.

Conclusion

The measurement of time varying, 3D hip, knee and ankle kinematics and knee and ankle moments during unplanned sidestepping were broadly equivalent between motion capture laboratories, but uncertainties in systematic bias should be further investigated and reduced. The dependent variables commonly used to describe an unplanned sidestep did not differ between motion capture laboratories.

Data availability statement

The raw data used for this study is not open. Data outputs can be made available upon request to the corresponding author and Hockey Australia.

Geolocation information

Data was collected at the University of Western Australia, Perth, Western Australia and Liverpool John Moores University, Liverpool, UK.

Funding disclosure statement

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Disclosure of interest

None of the authors have any conflicts of interest that could have biased the presentation and interpretation of the research presented.

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Discrete (0D) variable	LJMU Mean (std)	UWA Mean (std)	Mean Difference (LJMU – UWA)	*p*-value	95%CI
Change of direction angle (º)	28 (2.4)	23 (7.3)	5	0.070	-0.49 – 11.33
Velocity @ 0% stance ($m \cdot s^{-1}$)	4.2 (0.13)	4.2 (0.41)	0.0	0.620	-0.39 – 0.25
Velocity @ 100% stance ($m \cdot s^{-1}$)	3.8 (0.23)	3.9 (0.41)	-0.1	0.130	-0.46 – 0.07
Stance time (s)	0.23 (0.02)	0.25 (0.02)	-0.02	0.080	-0.04 – 0.002

Table 1: Variables selected to characterise an unplanned sidestepping task.

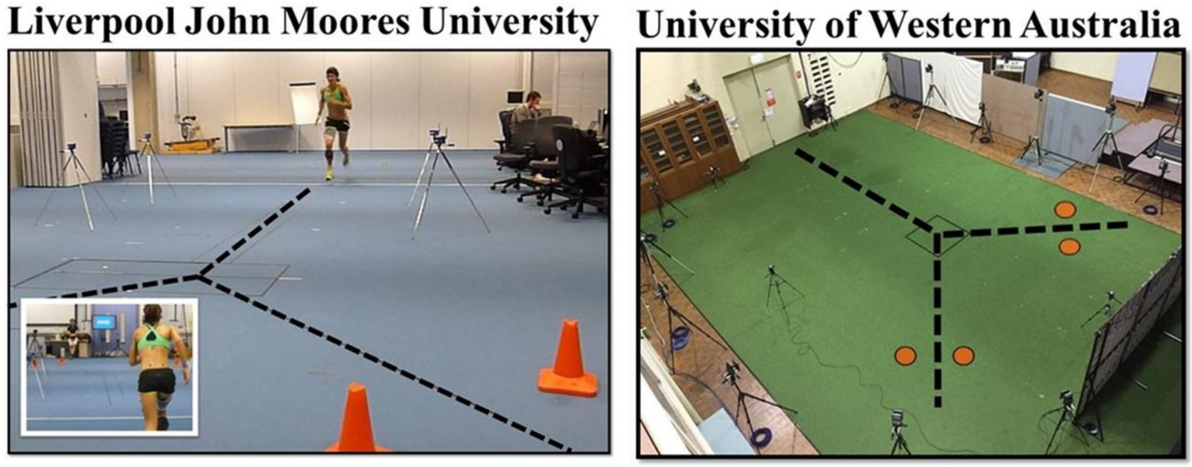

Figure 1: Overview of LJMU (*left*) and UWA (*right*) motion capture laboratories and unplanned sidestepping procedure.

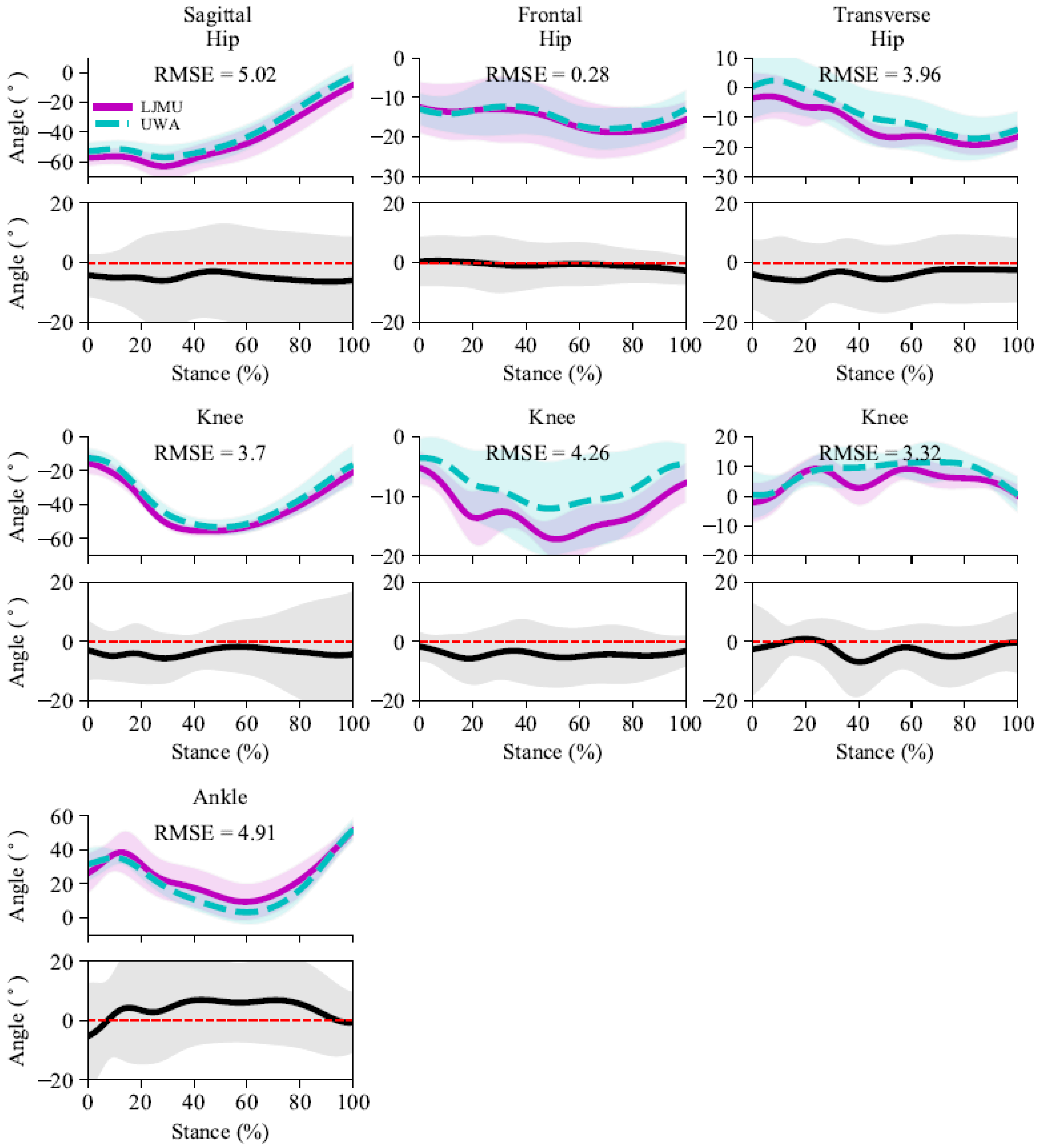

Figure 2: Time varying, 3D lower limb sidestepping joint kinematics during the stance phase of unplanned sidestepping (above) and the time-varying 1D 95% confidence interval surrounding the mean of the paired CI difference (below). RMSE embedded (above).

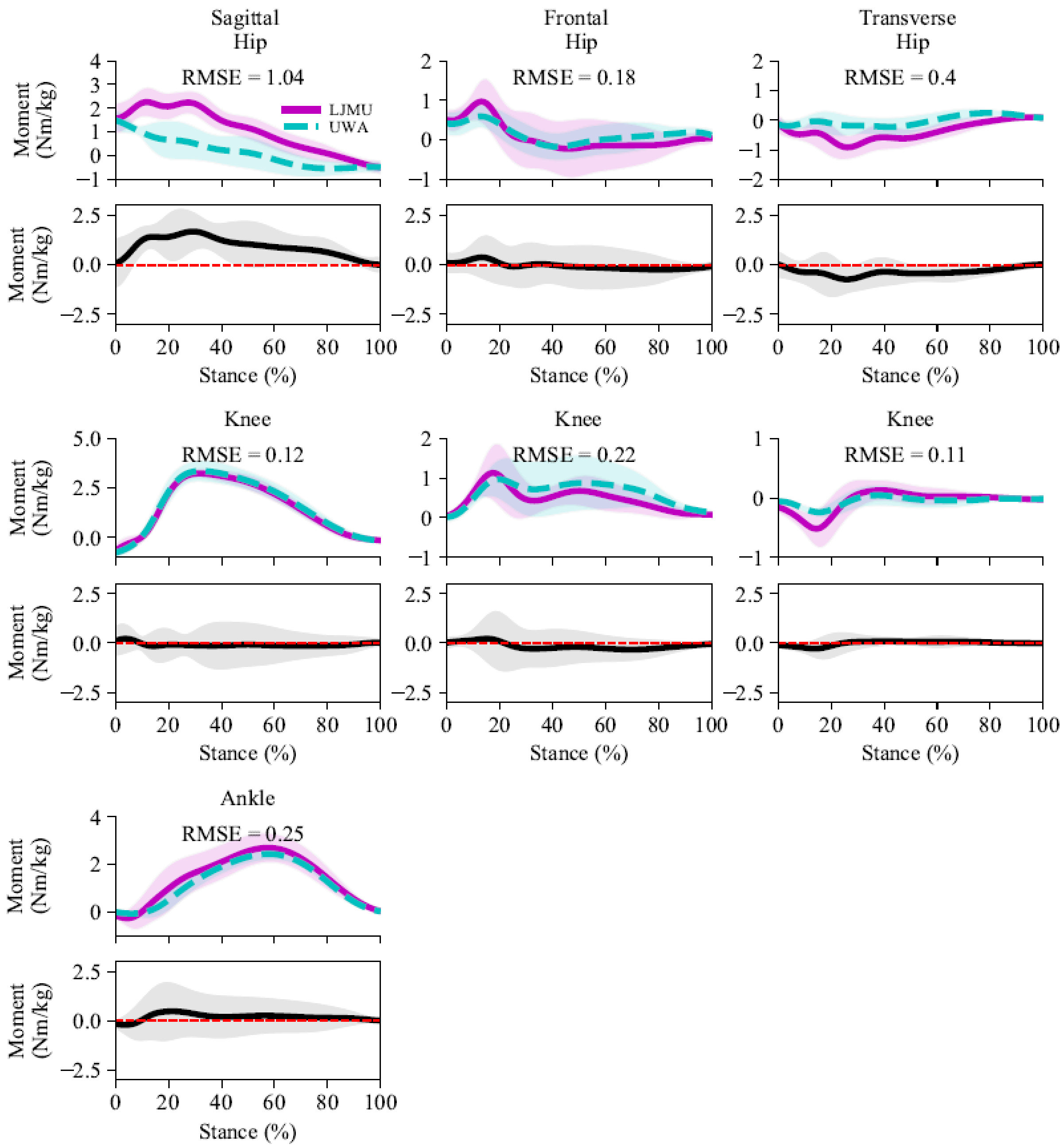

Figure 3: Time varying, 3D lower limb sidestepping joint moments during the stance phase of unplanned sidestepping (above) and the time-varying 1D 95% confidence interval surrounding the mean of the paired difference. RMSE embedded (above).