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Title: How Reliable are Lower Limb Biomechanical Variables During Running and Cutting Tasks

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Keywords: reliability; measurement error; kinetic; kinematic; run; cut.

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Abstract: The purpose of this study was to compare the within- and between-days reliability of lower limb biomechanical variables collected during running and cutting tasks. Methods: 15 recreational athletes, 7 males and 8 females, took part in three testing sessions, two sessions on the same day with an hour gap and another session one week later. Kinematic and kinetic data during running and 90° side step cutting tasks gathered using a ten-camera motion analysis system (Qualisys) and a force platform (AMTI) embedded into the floor. Results: During both tasks, within-day ICC values for joint angles (ICCrun = 0.63-0.94 and ICCcut = 0.63-0.96) were higher than between days (ICCrun = 0.51-0.72 and ICCcut = 0.42-0.83). Out of five moments tested in each task, within-day ICC values (ICCrun = 0.64-0.89 and ICCcut = 0.79-0.94) were higher than between days (ICCrun = 0.58-0.91 and ICCcut = 0.83-0.92). During running task, within and between-day SEM values for joint moments ranged between (0.07-0.39 NmKg) and between (0.98°-5.14°) for joint angles. While during cutting, SEM values for moments ranged between (0.13-0.56 NmKg) and between (1.73-5.15) for joint angle measurement. The GRF data, in both tasks, were more reliable (ICCrun ≥ 0.84 and ICCcut ≥ 0.88) as compared to angles (ICCrun ≥ 0.51 and ICCcut ≥ 0.42), and moments (ICCrun ≥ 0.58 and ICCcut ≥ 0.79) data. These findings are relevant to those undertaking intervention studies because of the potential for large measurement variability when examining certain variables, which would then require considerable changes in these variables to show "real" effects of the interventions beyond measurement error.

Abstract

The purpose of this study was to compare the within- and between-days reliability of lower limb biomechanical variables collected during running and cutting tasks. Methods: 15 recreational athletes, 7 males and 8 females, took part in three testing sessions, two sessions on the same day with an hour gap and another session one week later. Kinematic and kinetic data during running and 90° side step cutting tasks gathered using a ten-camera motion analysis system (Qualisys) and a force platform (AMTI) embedded into the floor. **Results**: During both tasks, within-day ICC values for joint angles (ICCrun = 0.63-0.94 and ICCcut = 0.63-0.96) were higher than between days (ICCrun = 0.51-0.72 and ICCcut = 0.42-0.83). Out of five moments tested in each task, within-day ICC values (ICCrun = 0.64-0.89 and ICCcut = 0.79-0.94) were higher than between days (ICCrun = 0.58-0.91 and ICCcut = 0.83-0.92). During running task, within and between-day SEM values for joint moments ranged between (0.07-0.39 NmKg) and between (0.98°-5.14°) for joint angles. While during cutting, SEM values for moments ranged between (0.13-0.56 NmKg) and between (1.73-5.15) for joint angle measurement. The GRF data, in both tasks, were more reliable ($ICCrun \geq 0.84$ and $ICCcut \geq 0.88$) as compared to angles ($ICCrun \geq 0.51$ and $ICCcut \geq 0.42$), and moments ($ICCrun \geq 0.58$ and $ICCcut \geq 0.79$) data. These findings are relevant to those undertaking intervention studies because of the potential for large measurement variability when examining certain variables, which would then require considerable changes in these variables to show “real” effects of the interventions beyond measurement error.

Key words

Reliability; measurement error; kinetic; kinematic; run; cut

1. *Introduction*

The cutting manoeuvre has been shown to be a mechanism that can cause non-contact anterior cruciate ligament injuries (Besier, Lloyd, Cochrane, & Ackland, 2001; Havens & Sigward, 2014a; Vanrenterghem, Venables, Pataky, & Robinson, 2012). Previous literature has assessed lower limb biomechanics during side-step cutting tasks using three-dimensional (3D) motion analysis (Havens & Sigward, 2014b; Houck, Duncan, & Haven, 2005; Imwalle, Myer, Ford, & Hewett, 2009; Jones, Herrington, Munro, & Graham-Smith, 2014; Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2012; Kristianslund & Krosshaug, 2013; Marshall et al., 2014; Pollard, Sigward, & Power, 2007). When undertaking assessments of movement it is important to understand the reliability of the measuring tools being used (Rankin & Stokes, 1998). A key consideration when using movement analysis techniques is the ability to measure biomechanical variables consistently in individuals on the same day or even after several days. If assessment is going to be used to assess a cutting technique following a training intervention, for example, it is critical to understand the level of potential measurement error, so that the true change brought about by training can be seen, as opposed to change related to random measurement errors.

Recently, investigators have examined the reliability of biomechanical variables during cutting tasks (Besier et al., 2001; Sankey et al., 2015; Stephenson et al., 2012). The majority of studies standardise the cutting angle at or around 45° (Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007; McLean, Huang, & van den Bogert, 2005; McLean, Lipfert, & van den Bogert, 2004; O'Connor & Bottum, 2009; Pollard, Davis, & Hamill, 2004; Sigward & Powers, 2006). This angle is acute enough to require substantial deceleration, but shallow enough for the change in direction to be achieved within the time constraint of a single foot contact. In Premier League football matches, Bloomfield et al. (2007) report that when athletes changed direction, they frequently performed cutting manoeuvres at angles of between 90 and 180 degrees, which increases the stress placed on the knee.

A 90° sidestep cut has a very different momentum profile than a 45° degree sidestep cut or forward run (Scot et al., 1995), and to date there are no reliability studies available for this task. Also, no studies have looked at the reliability and associated measurement error of lower limb joint kinematic and kinetic variables during running and 90° sidestep cutting tasks together, i.e. in the same cohort. Without measurement error values, changes in performance cannot be evaluated properly as it is not known whether these changes may be attributed to the intervention or to measurement errors, such as marker position, marker re-application, static alignment and task difficulty (Alenezi, Herrington, Jones, & Jones, 2014; Ferber, Davis, Williams, & Laughton, 2002; Malfait et al., 2014). The aim of this study was, therefore, to assess the within- and between-days reliability of lower limb biomechanical data collected during running and 90° sidestep cutting tasks.

2. Methods

2.1. *Participants*

Fifteen recreational athletes, eight females (age 26 ± 3.5 years; height 163 ± 5.4 cm; mass 63 ± 8.0 kg) and seven males (age 25 ± 6.4 years; height 171 ± 6.7 cm; mass 69.7 ± 10.7 kg), took part in this study. The participants were required to have been free from lower limb injury for at least six months, and to have no history of lower limb surgery. A recreational athlete is defined as participating in physical activity for at least one hour, three times per week. All participants gave informed consent, and the University of Salford ethical committee approved the study.

2.2. Procedure

A ten-camera motion analysis system (Pro-Reflex, Qualisys, Sweden), sampling at 240 Hz, and a force platform embedded into the floor (AMTI, USA), sampling at 1200 Hz, were synchronised to collect kinematic and kinetic data during the support phase of running and cutting tasks. Participants were tested twice during their first visit (1st and 2nd sessions), with a one-hour gap between sessions to investigate within-day reliability. Participants were then tested one week later (3rd session), at the same time of day, to assess the between-days reliability of using 3D motion capture to measure biomechanical variables during RUN and CUT tasks. Before each session, participants were allowed practise each of the four tasks until they felt comfortable; this was typically two to three trials. Participants started with five minutes of low intensity warm-up on a cycle ergometer. After familiarisation, participants were required to complete three successful repetitions of each task.

Figure (1) Data collection set-up

Figure 1 about here

Before testing, mass and height were measured and the subjects were fitted with standard training shoes (New Balance, UK) to control the shoe-surface interface. Reflective markers (14 mm) were attached with adhesive tape to the participants' lower extremities over the following landmarks; anterior superior iliac spines, posterior superior iliac spines, iliac crest, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, posterior calcanei, and the head of the first, second and fifth metatarsals. Tracking markers were secured to technical clusters on the thigh and shank with elastic bands. Foot markers were placed on the shoes, and the same person attached these markers for all participants. The calibration anatomical systems technique (CAST) was used to determine the six degrees of freedom movement of each segment and anatomical significance during the movement trials (Cappozzo, Catani, Croce, & Leardini, 1995). CAST has the advantage of offering improved anatomical relevance, compared to the modified Helen Hayes marker set, and it attempts to reduce skin-movement artefacts by attaching cluster markers to the centre of segments rather than single markers on the joints, as in the Helen Hayes model (Collins et al., 2009; Kadaba et al., 1989). The markers were removed and replaced for within-day reliability (1st and 2nd sessions) and obviously removed and replaced for between-day sessions (1st and 3rd sessions).

Due to limited laboratory space, the cutting manoeuvre could only be performed with the subjects' right leg. Thus, reliability was only assessed for right leg variables for both tasks. During running, subjects were required to run at their perceived maximal velocity and to make contact with the force platform with their right leg whilst running along a 10 m runway. For the cutting task, subjects were required to contact the force platform, immediately turn 90° to the left and run three metres in that direction through a second timing gate. Cones were placed at a 90-degree angle from the original movement direction and used to guide the participants to cut at an angle of 90° (Fig. 1).

To ensure consistent speeds for both tasks, a set of Brower timing lights (Draper, UT) were used. These were set at approximately hip height for all participants, as previously suggested (Jones et al., 2014; Yeadon, Kato, & Kerwin, 1999), to ensure that only one body part, such as the lower torso, broke the beam. The time to complete the run and cut tasks was used to monitor each subject's performance on each test occasion. The speed was then calculated by dividing distance by time. In order to compare the findings with the literature, participants were asked to repeat their trial if their speed fell below 4 m/sec. for running and 3 m/sec. for cutting tasks.

Participants were required to complete three successful repetitions of each task, and they were given about one to one and a half minutes between trials to diminish the effect of fatigue (Cortes et al., 2010). A trial was considered successful if the right leg stance phase occurred on the force platform, stayed within the cutting pathway designated by the cones, and maintained a consistent approach speed.

2.3. Data Processing

Visual3D motion capture software (Version 4.21, C-Motion Inc. USA) was used to process kinematic and kinetic data. Motion and force plate data were filtered using a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12 Hz and 25 Hz, respectively, with cut-off frequencies being selected based on a residual analysis (Yu B, Gabriel D, Noble L, & KN, 1999). There is no consensus on whether to adopt the same cut-off frequency for both sets of data, hence we chose to base our frequencies on a residual analysis and not to over-smooth kinetic data.

All lower extremity segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (Dempster, Gabel, & Felts, 1959). Joint kinematic angles were processed using an X–Y–Z Euler rotation sequence, where X equals flexion-extension, Y abduction-adduction, varus-valgus and Z internal-external rotation. Joint kinetic data were calculated using three-dimensional inverse dynamics, and joint moment data were normalised to body mass and presented as external moments referenced to the proximal segment. Kinematic and kinetic data were normalised to 100% of the right leg contact phase as defined from right leg initial contact to toe-off. Initial contact was defined as the instant after ground contact, when the vertical GRF was higher than 20 N, while end of contact was defined as the point when the vertical GRF subsided below 20 N (Jones et al., 2014). Peak values are often variables of interest when making statistical and clinical comparisons.

On the basis of their frequent use in relation to possible biomechanical risk factors for anterior cruciate ligament (ACL) and patellofemoral pain syndrome (PFPS) injury studies (Padua and Distefano, 2009; Stefanyshyn et al., 2006; Hewett et al., 2005), the following discrete variables were calculated for the right leg during each trial:

a. Peaks of hip-flexion, adduction and internal-rotation angles and moments;
b. Peaks of knee-flexion, valgus and internal-rotation angles;
c. Peaks of knee-flexion and valgus moments;
d. Peak ankle dorsiflexion angle and moment;
e. Peak vertical ground-reaction force (VGRF).

2.4. Statistical Analysis

The means of three trials from the first and second sessions were used for within-day reliability and the means of the first and third sessions for between days. Intra-class correlation coefficients (ICC), model (3, k), and the level of ICC values were interpreted according to the criteria set by Coppieters et al. (2002), (less than 0.40 is poor, between 0.40 and 0.70 is fair, between 0.70 and 0.90 is good, more than 0.90 is excellent).

ICC values alone cannot be interpreted clinically because they do not provide any indication of the level of disagreement between measurements (Rankin & Stokes, 1998). Therefore, standard error of measurement (SEM) and smallest detectable difference (SDD) were calculated. SEM was obtained using the formula: SD*√1-ICC (Denegar & Ball, 1993). SDD was calculated using the formula: SDD =1.96*(√2)*SEM (Kropmans, Dijkstra, Stegenga, Stewart, & de Bont, 1999). Statistical analysis was performed in SPSS (version 21).

3. Results

The results obtained from the cutting and running tasks are presented in Tables 1 and 2, respectively. During the cutting task, within-day ICC values for kinematic and kinetic variables ranged from 0.63–0.96, while between-day ICCs ranged from 0.42–0.92. SEM values ranged from 1.73–5.15° for all reported angles and from 0.14–0.56 Nm-kg for moments. Knee internal rotation angle for between-days measurement was the poorest variable with an ICC value of 0.40. Hip internal rotation angle recorded the highest SEM and SDD values for both within-day and between-days reliability (SEM= 3.81° & 5.15°; SDD= 10.56° & 14.27°, respectively). The average of the participants' speeds during the cutting trials was 3.8 ± 0.4 m.s.1 with ICC values of between 0.89 and 0.94.

Table (1) Within-day & between-days ICC (95% CI), Mean, and SEM values for the cutting task

Table (1) about here

Figure (2) Ensemble average plot of knee valgus motion for the cutting task.

Figure (2) about here

During the running task, within-day ICC values for kinematic and kinetic data collected during running trials ranged from 0.64–0.94 while between-days ICCs ranged from 0.51–0.91. SEM values ranged from 1.98–5.14° for angles and from 0.09–0.58 Nm-kg for moments. Hip flexion angle recorded the highest SEM and SDD values for both within-day and between-days reliability (SEM= 5.14° & 4.74°; SDD= 14.24° & 13.13°, respectively). The average speed during running was 4.99± 0.5 m·s^{-1} with ICC values of 0.91–0.95.

Table (2) Within-day & between-days ICC (95% CI), Mean, and SEM values during running task

Table (2) about here

Figure (3) Ensemble average plot of knee valgus motion during the running task.

Figure (3) about here

4. Discussion

The objective of the study was to assess the within-day and between-days reliability of biomechanical variables during running and cutting tasks in non-elite individuals. In the present investigation, the between-day ICC values for kinematic, kinetic and GRF data, for both tasks, were lower than within-day values. Other researchers have reported similar findings for a 45° cutting manoeuvre (Sankey et al., 2015) and running (Diss, 2001; Ferber et al., 2002; Queen, Gross, & Liu, 2006).

The ICC values for vertical GRF reported in the current study are comparable to those reported in Ferber and colleagues' study (2002). Unsurprisingly, vertical GRF data were more consistent than joint angles and moments, since GRF data are representative of the sum of all segmental masses and accelerations (Ferber et al., 2002; Winter, 1984), and so less variability will be seen as compared to kinetic or kinematic data. Also, no markers are needed to gather GRF data and so there is no marker placement error (Ferber et al., 2002).

SEM values are very useful for clinicians to determine individual improvement (Denegar & Ball, 1993). This study provides SEM and SDD reference values for running and cutting tasks that may be useful for evaluating intervention outcomes (Tables 1 and 2). Hip flexion angle during the RUN task recorded the highest SEM values, especially for between-days measurement (SEM= 4.7°); however, this represents 8.5% compared to the mean value of this variable (Mean= 55.4°). This may be explained by the larger range of motion in the sagittal plane compared to other planes. None of the aforementioned running studies (Ferber et al., 2003; Queen et al., 2006) include the hip flexion angle in their analyses. In the cutting task, the lowest reliability is reported for hip internal rotation (ICC 0.51; SEM 5.15°), which suggests large within-subject differences during between-day measurement. However, it appears that these differences are equally and randomly distributed across the subjects, resulting in similar mean data (6.8° vs 6.5°).

Several factors influence both within-day and between-days reliability, such as skin marker movement, referenced static alignment, and task difficulty (Ferber et al., 2002; Ford, Myer, & Hewett, 2007). Kadaba et al. (1989) attribute the variability of between-days measures to marker reapplication. In this study, the same investigator attached the markers in all trials. The decreased between-days ICC values indicate that differences in marker replacement influence the consistency even when controlling for the tester. Hence to reduce this variability within this study, the CAST marker based protocol (1995) was used. This protocol has the advantage of offering improved anatomical relevance compared to the modified Helen Hayes marker set (Collins et al., 2009; Kadaba et al., 1989), as it attempts to reduce skin movement artefacts by attaching cluster markers to the centre of segments rather than single markers on the joints, as in the Helen Hayes model (Collins, 2009). Noehren et al. (2010) attempted to improve between-days reliability by using a marker placement device. They found that the largest reduction in SEM values was in the transverse plane during running tasks (reducing SEM to 57% and improving ICC by 7%). Future research should focus on this issue and how to improve the reliability of knee-rotation measurements taken during cutting tasks.

Another possible source of variability could stem from the differing cut-off frequencies used for kinematic and kinetic data (Kristianslund, Krosshaug, & van den Bogert, 2012). Since there is no consensus on whether to adopt the same cut-off frequency for both sets of data, we chose to base our frequencies on residual analysis and not to over-smooth the kinetic data. Future studies should investigate how minor changes in the position of markers and cut-off frequencies influence the variables examined within this study, to provide clarity on this matter.

The generalisability of these findings is subject to certain limitations. For instance, these results only apply to our laboratory settings and models, though they are consistent with those previously reported; these, along with an individual's ability to place markers, could affect the results obtained in other laboratories. It must be acknowledged that there may be differences between the laboratory environment and the actual performance of study tasks. Although a familiarisation session was conducted with all participants, running and changing direction wearing standard trainers on a mondo running surface would not have been as natural for these individuals as actual sports. A further limitation is that an uninjured population was examined; but given the tests were used as screening tasks, this should be beneficial to investigators carrying out similar research. The reliability of these functional tests in a population with lower extremity injuries, such as ACL tear and patellofemoral pain syndrome (PFPS), needs further investigation, since ACL and PFPS have been linked to excessive hip adduction and internal rotation, and to knee valgus and external rotation during different functional tasks (Hewett, Myer, & Ford, 2004; Willson & Davis, 2008).

4. Conclusion

The current study demonstrates that certain variables show good to excellent consistency, both within session and between sessions, whereas others such as running hip adduction angle and knee internal rotation angle for both tasks do not. These findings are relevant to those undertaking intervention studies because of the potential for large measurement variability when examining certain variables, which would then require considerable changes in these variables to show the “real” effects of interventions over and above measurement errors.

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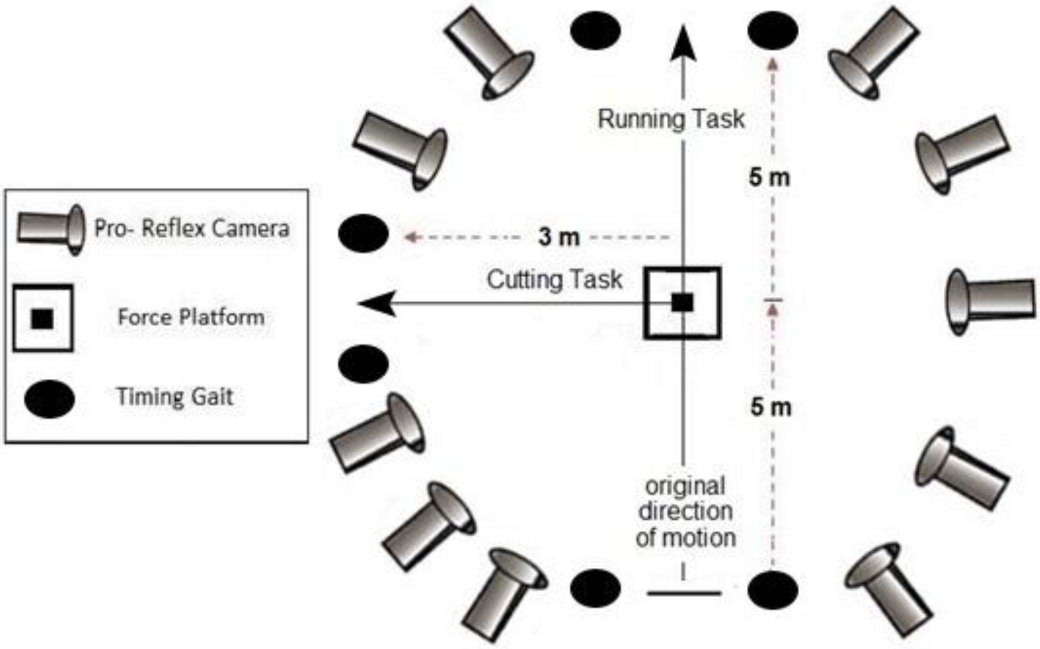
Figure

Figure 1. Data capture set-up



Table

Table (1) Within- & between-day ICC (95%CI), Mean, and SEM values during cutting task

Variables	**Within-day**				**Between-days**			
	ICC (95%CI)	Mean	SEM	SDD	ICC (95%CI)	Mean	SEM	SDD
Joint Angles (°)								
Hip Adduction	0.65 (0.23-0.87)	-7.15	3.37	9.14	0.60 (0.15-0.85)	-7.84	3.02	8.37
Hip Flexion	0.93 (0.81-0.98)	48.41	2.49	6.90	0.75 (0.40-0.91)	49.1	4.98	13.8
Hip Int. Rot.	0.80 (0.50-0.93)	6.84	3.81	10.56	0.51 (0.02-0.80)	6.51	5.15	14.2
Knee Valgus	0.93 (0.81-0.98)	-11.8	1.73	4.79	0.79 (0.48-0.92)	-11.6	3.02	8.37
Knee Flexion	0.96 (0.89-0.99)	66.26	2.04	5.65	0.83 (0.57-0.94)	65.9	4.16	11.5
Knee Int. Rot.	0.63 (0.19-0.86)	7.31	2.71	7.51	0.42 (-0.1-0.76)	5.48	4.09	11.3
Dorsiflexion	0.88 (0.68-0.96)	30.95	2.24	6.20	0.80 (0.50-0.93)	30.2	3.82	10.5
Moments (Nm/Kg)								
Hip Adduction	0.79 (0.48-0.92)	-0.76	0.22	0.60	0.88 (0.68-0.96)	-0.81	0.13	0.36
Hip Flexion	0.94 (0.83-0.98)	-2.70	0.27	0.74	0.84 (0.59-0.94)	-2.91	0.56	1.55
Knee valgus	0.93 (0.81-0.98)	1.43	0.18	0.49	0.92 (0.78-0.97)	1.40	0.20	0.55
Knee Flexion	0.82 (0.54-0.94)	3.30	0.16	0.44	0.83 (0.57-0.94)	3.25	0.18	0.49
Dorsiflexion	0.88 (0.68-0.96)	-2.46	0.14	0.38	0.87 (0.66-0.95)	-2.46	0.16	0.44
Force (*body weight)								
Vertical GRF	0.95 (0.86-0.98)	3.09	0.18	0.49	0.88 (0.68-0.96)	3.08	0.28	0.77

Table

Table (2) Within- & between-day ICC (95%CI), Mean, and SEM values during run task

Variables	**Within-day**				**Between-days**			
	ICC (95%CI)	Mean	SEM	SDD	ICC (95%CI)	Mean	SEM	SDD
<u>Joint Angles (°)</u>								
Hip Adduction	0.75 (0.40-0.91)	17.3	1.99	5.51	0.51 (0.02-0.80)	17.1	2.49	6.90
Hip Flexion	0.74 (0.38-0.90)	54.7	5.14	14.2	0.65 (0.23-0.87)	55.3	4.74	13.1
Hip Int. Rot.	0.76 (0.42-0.91)	2.54	2.46	6.81	0.72 (0.35-0.90)	3.03	3.08	8.53
Knee Valgus	0.94 (0.83-0.98)	-7.04	0.98	2.71	0.61 (0.16-0.85)	-7.23	2.41	6.68
Knee Flexion	0.63 (0.19-0.86)	53.5	3.68	10.2	0.67 (0.26-0.88)	53.7	3.23	8.95
Knee Int. Rot.	0.74 (0.38-0.90)	5.25	2.84	7.87	0.58 (0.12-0.84)	3.47	3.62	10.0
Dorsiflexion	0.78 (0.46-0.92)	33.1	1.98	5.48	0.71 (0.33-0.89)	33.0	2.42	6.70
<u>Moments (Nm/Kg)</u>								
Hip Adduction	0.64 (0.21-0.86)	-2.38	0.39	1.08	0.69 (0.29-0.88)	-2.36	0.30	0.83
Hip Flexion	0.81 (0.52-0.93)	-2.84	0.44	1.21	0.83 (0.57-0.94)	-2.84	0.38	1.05
Knee valgus	0.85 (0.61-0.95)	0.36	0.07	0.19	0.72 (0.35-0.90)	0.35	0.09	0.24
Knee Flexion	0.70 (0.31-0.89)	2.63	0.22	0.60	0.58 (0.12-0.84)	2.67	0.25	0.69
Dorsiflexion	0.89 (0.70-0.96)	-3.06	0.15	0.41	0.91 (0.75-0.97)	-3.04	0.14	0.38
<u>Force (*body weight)</u>								
Vertical GRF	0.92 (0.78-0.97)	2.69	0.14	0.38	0.84 (0.59-0.94)	2.66	0.18	0.49

Figure (2)

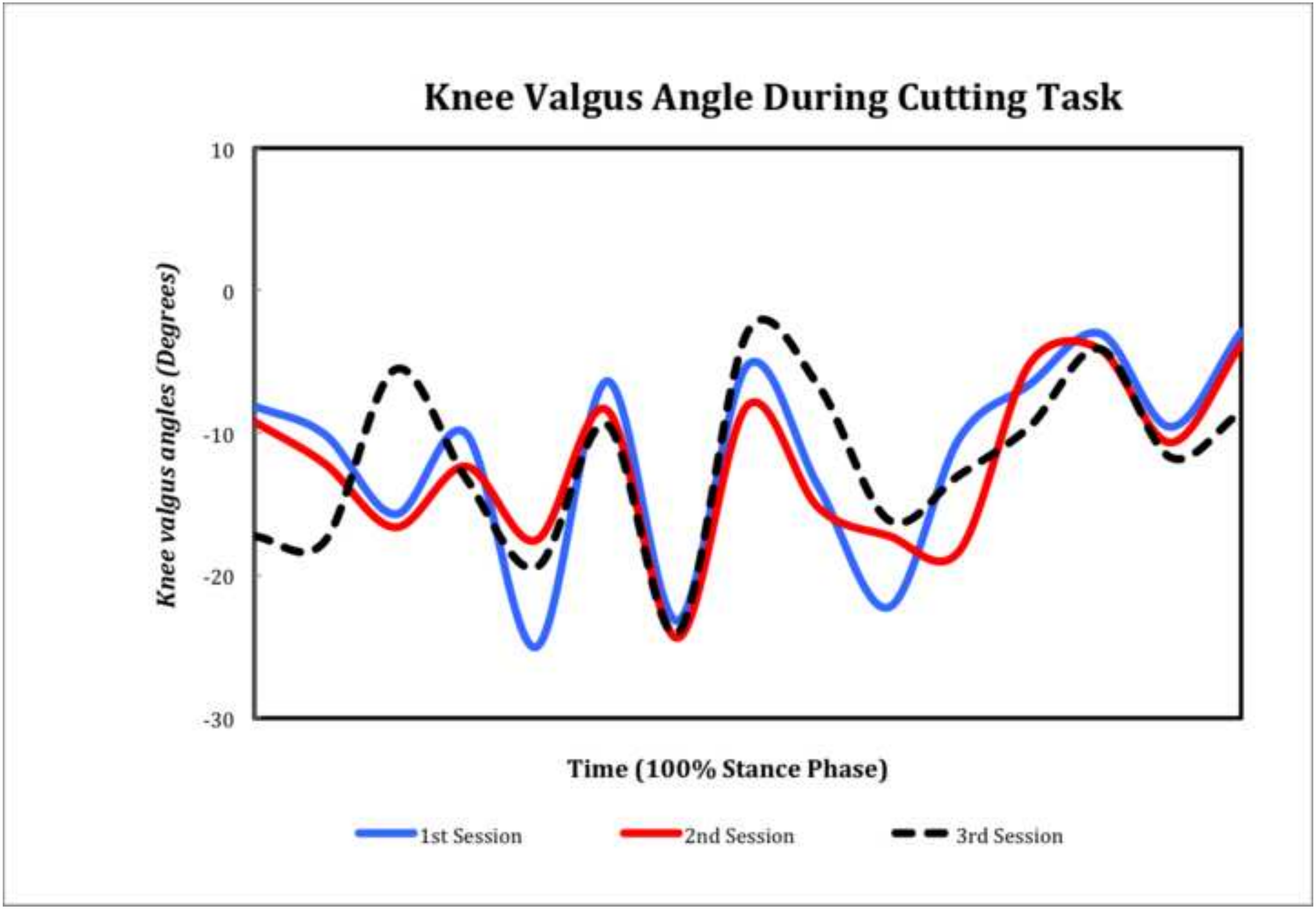

Knee Valgus Angle During Cutting Task
10
0
-10
-20
-30
Knee valgus angles (Degrees)
Time (100% Stance Phase)
1st Session
2nd Session
3rd Session

Figure (3)

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