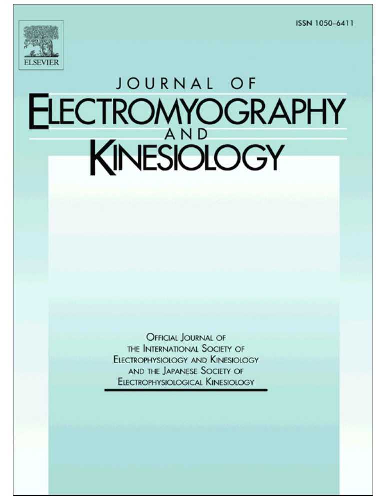

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Braking Characteristics during Cutting and Pivoting in Female Soccer Players.

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Introduction

The ability to change direction quickly and efficiently is an important quality for many different sports [Sheppard and Young, 2006]. Changing direction manoeuvres such as cutting and pivoting have been associated with non-contact anterior cruciate ligament (ACL) injuries [Boden, 2000; Faude *et al*., 2005; Olsen *et al*., 2004]. During change of direction manoeuvres there is a propensity to generate relatively high knee abduction and rotational moments [McLean *et al*., 2003] when the foot is planted which could lead to increased ACL strain [McLean *et al*., 2003; McLean *et al*., 2004; Shin *et al*., 2009; Shin *et al*., 2011] and subsequent injury. Thus, an understanding of how to effectively brake and change direction is important not only for performance, but also injury prevention.

Several studies have explored relationships between technique variables and knee abduction moments during cutting [Dempsey *et al*., 2007; Dempsey *et al*. 2009; McLean *et al.*, 2005; Sigward and Powers, 2007; Kristianlunds *et al*., 2014, Jones et al., 2015] and pivoting [Jones et al., 2016]. However, a potential limitation of previous research into optimal cutting technique is that many of these studies [Dempsey *et al*., 2007; Dempsey *et al*. 2009; Kristianlunds *et al*., 2014; McLean *et al*., 2005; Sigward and Powers, 2007] have focused on the joint kinematics and kinetics of the final contact during a change of direction task. The final contact can be defined as the phase during a cut or pivot when an individual makes contact with the ground and initiates movement into a different direction. A preliminary study [Graham-Smith *et al*., 2009] found that the penultimate contact (the 2nd last foot contact with the ground prior to moving into a new intended direction) prior to the final contact resulted in greater peak vertical and horizontal (anterior-posterior) ground reaction forces (GRF) and external knee flexor moments compared to final contact during a 180° turn and that greater peak horizontal braking force at penultimate contact was related to faster turn times.

With regard to deceleration movements in soccer, Bloomfield *et al*., [2007b] found the mean duration of decelerations was 0.82s, with 72.2% less than 1 second and 95.5% less than 2 seconds. Given that typical contact times for cutting and pivoting are 0.319 ± 0.06 s [Kristianlunds *et al*., 2014] and 0.61 ± 0.08 s [Graham-Smith *et al*., 2009], respectively; this suggests that deceleration most often takes place over a series of steps, rather than just the final contact and highlights the need to investigate penultimate contact to gather a greater understanding of braking strategy involved in cutting and pivoting. In support of this, Nedergaard et al. [2014] using accelerometry found that average trunk accelerations and peak joint flexion velocities via 3D motion analysis were larger in the preceding two footfalls compared to the final footfall of a 135° change of direction task; highlighting the importance of the preceding footfalls in the deceleration strategy of change of direction tasks with greater angles. There is a lack of studies comparing kinematics (joint angles) and kinetics (GRF's and joint moments) between final contact and the preceding contacts of cutting and pivoting. Moreover, the role of penultimate contact during cutting and pivoting may vary due to the different task demands with cutting involving a deceleration before shifting momentum into a new direction, whereas pivoting involves decelerating to a stop and then re-accelerating in the opposite direction. Thus, further investigation into both tasks is warranted.

Given that approach velocity has been shown to influence knee abduction moments during cutting [Vanrenterghem *et al*., 2012], analysis of the penultimate contact may provide more insight into the optimal technique for changing direction for reduced injury risk. Theoretically, if the majority of an individual's velocity and thus forward momentum can be reduced during the penultimate contact through greater braking forces, this may potentially lower GRF's and subsequent knee abduction moments during the final contact where injuries can occur [Boden *et al*., 2000; Olsen *et al*., 2004], due to a relatively lower centre of mass velocity at this point. However, there are a lack of studies evaluating such a hypothesis. Jones et al., [2015, 2016] considered a ratio of peak horizontal GRF between final and penultimate contact during investigations of technique determinants of peak knee abduction moments during cutting and pivoting in female soccer players, respectively. No relationship was observed between this ratio and peak knee abduction moments during cutting [Jones et al., 2015] and pivoting [Jones et al., 2016]. However, the authors did not consider additional variables of average horizontal braking force and impulse which may provide more insight into braking during the penultimate contact. For example, greater average horizontal braking force over the weight acceptance phase, would generate greater impulse, and greater impulse over this phase would lead to a greater reduction in momentum (i.e., velocity). The aim of the study was two-fold; firstly to explore kinematic (lower limb joint angles) and kinetic (GRF's and moments) differences between penultimate and final contact of cutting and pivoting in female soccer players. Secondly, to investigate the association between horizontal force-time characteristics during penultimate contact and the ratio of these variables between final and penultimate contact to peak knee abduction moments during the weight acceptance phase of final contact of both manoeuvres.

Methods

Participants

Twenty-two female soccer players (mean ± *SD*; age: 21 ± 3.1 years, height: 1.68 ± 0.07 m, and mass: 58.9 ± 7.3 kg) participated in the study. All players were registered with Soccer clubs playing in the second tier of English Women's Soccer. Written informed consent was attained from all participants and approval for the study was provided by the University's ethical committee. The study was conducted in accordance with the Declaration of Helsinki.

Research Design

Testing took place on an indoor synthetic running surface. Each participant was required to attend the lab on two separate occasions. The first occasion was a familiarisation session on the protocols used in the study with data collected on the subsequent session. All participants performed two change of direction tasks; a 90º cut and pivot (180º turn). A change of direction task involves changing direction to a predefined direction after initially running forward. The 90º cut involved running towards two force platforms, prior to the turn the participant ran through, a set of timing lights 5 m from the centre of the last platform (Figure 1). The participant then made contact with the 2nd force platform with the right foot and immediately cut 90º to the left and ran through a second set of timing lights 3 metres away. The timing lights provided the time to complete the 90º course. For the pivot, the subjects approached in the same manner, but the participant turned back 180º to the original starting position once contacting the 2nd force platform with the right leg. The timing cells were re-configured to give a time to complete the 180° course.

During the test session all participants performed a minimum of 10 trials of cutting and pivoting. Total time to complete the tasks was measured using a set of Brower timing lights (Draper, UT) set at approximate hip height for all participants as previously recommended [Yeadon *et al*., 1999], to ensure that only one body part, such as the lower torso, breaks the beam. Each trial needed to achieve an appropriate time [cut; 1.85s ± 10%, pivot; 2.65s ± 10%], whilst contacting the central portion of the 2nd platform during final contact to ensure a homogeneous distance of travel between trials and without prior stuttering or prematurely turning prior to final contact. Verbal feedback was provided to rectify any of the abovementioned aspects on subsequent trials. The times were selected based on pilot work and was used to control for performance of the tasks within and between participants. In addition, for each trial the horizontal velocity in the direction of motion of the right hip joint centre was calculated over the 10 frames prior to foot contact of the penultimate contact to determine approach velocity in accordance with McLean *et al.* [2005]. This retrospective analysis was conducted to ensure that each participants trial achieved a target approach velocity of between 4 and 5 $m{\cdot}s^{-1}$ for cutting and between 3.6 to 4.4 $m{\cdot}s^{-1}$ for pivoting. These target approach velocities were selected based on velocities recorded in several previous studies [McLean *et al*., 2004; McLean *et al*., 2005; Cortes *et al*., 2011] and previous pilot data collected in this lab.

For both tasks each participant started approximately 5 metres behind the first set of timing lights. Some flexibility was allowed for the exact starting point for each participant to allow for the participants differing stride pattern as they approached the 2 force platforms. Each subject was allowed time prior to data collection to identify their exact starting point to ensure an appropriate force platform contact.

Procedures

Reflective markers were placed on the following body landmarks; mid-clavicle, 7th cervical vertebrae, right and left; shoulder, iliac crest, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial epicondyle, lateral epicondyle, lateral malleouli, medial malleouli, heel, 5th, 2nd and 1st metatarsal heads using double-sided adhesive tape. Participants also wore a 4 marker 'cluster set' (4 retro-reflective markers attached to a light weight rigid plastic shell) on the trunk, pelvis, right and left; thigh and shin, to approximate motion of these segments during dynamic trials. The use of clusters is suggested to be more accurate and practical for tracking motion than individual skin markers [Angeloni *et al*., 1993], with four markers suggested as optimal [Cappozzo *et al*., 1997; Manal *et al*., 2000]. The thigh and shank cluster sets were attached using Velcro elasticated wraps, whereas a lycra 'crop top' and elastic belt were used to attach the trunk and pelvis cluster sets, respectively.

Three dimensional motions of these markers were collected whilst performing each athletic task using Qualysis 'Pro reflex' (Model number: MCU 240, Gothenburg, Sweden) infrared cameras (240Hz) operating through Qualysis Track Manager software (C-motion, version 3.90.21, Gothenburg, Sweden). GRF's were collected from two 600 mm × 900 mm

AMTI (Advanced Mechanical Technology, Inc, Watertown, MA) force platforms (Model number: 600900) embedded into the running track sampling at 1200Hz.

From a standing trial, a lower extremity and trunk 6 degrees of freedom kinematic model was created for each participant, including pelvis, thigh, shank and foot using Visual 3D software (C-motion, version 3.90.21). This kinematic model was to quantify the motion at the hip, knee and ankle joints using a Cardan angle sequence x-y-z [Grood and Suntay, 1983]. The local coordinate system was defined at the proximal joint centre for each segment. The static trial position was designated as the subject's neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. Segmental inertial characteristics were estimated for each participant [Dempster, 1955]. The model utilised a CODA pelvis orientation [Bell *et al*., 1989] to define the location of the hip joint centre. The knee and ankle joint centres were defined as the mid-point of the line between lateral and medial markers. Lower limb joint moments were calculated using an inverse dynamics approach [Winter, 1990] through Visual3d software (C-motion, version 3.90.21). Joint moments are defined as external moments.

A minimum of 4 trials were used in the analysis of each participant [Sigward and Power, 2007; Dempsey *et al*., 2007; Dempsey *et al.,* 2009; Cortes *et al*., 2011] based on visual inspection of the motion files. The trials were time normalised for each subject to 101 data points with each point representing 1% of the contact phase (0 to 100% of contact) of the cutting and pivoting tasks. Initial contact was defined as the instant after ground contact that the vertical GRF was higher than 20 N and end of contact was defined as the point where the vertical GRF subsided past 20 N. The weight acceptance phase was defined as the instant of initial contact to the point of maximum knee flexion. Using the pipeline function in visual 3D, joint coordinate and force data were smoothed with a Butterworth low pass digital filter with cut-off frequencies of 12Hz and 25Hz, respectively. Cut off frequencies were selected based on a residual analysis [Winter, 1990] and visual inspection of the data.

For comparisons between penultimate and final contact, peak hip, knee and ankle dorsi-flexion angles, peak and average hip, knee and ankle moments during the weight acceptance phase were quantified in MS excel. As whole-body deceleration takes place in the sagittal plane during these manoeuvres, only sagittal plane joint angles and moments are considered here. Peak and average vertical and horizontal (anterior-posterior) GRF's and horizontal braking impulse (net area under the Fy force-time curve during the weight acceptance phase) during this phase were also quantified along with total ground contact time.

In addition to comparisons between penultimate and final contact for the abovementioned variables, the study aimed to explore the relationships between horizontal (anterior-posterior) force characteristics during penultimate contact and the ratio between final and penultimate contact for average horizontal (anterior-posterior) force and horizontal braking impulse to peak knee abduction moments during the weight acceptance phase of final contact.

Statistical Analysis

All statistical analysis was performed in SPSS for windows v17 (Chicago, Ill). Normality for each variable was examined using a Shapiro-Wilks test. Paired sample t-tests were used for normally distributed data to compare peak and average vertical and horizontal GRF's, horizontal braking impulse and peak and average lower limb joint moments between the weight acceptance phase of penultimate and final contact for both manoeuvres. Otherwise Wilcoxon signed ranks tests were used for data that did not meet the assumption of normality.

Effect sizes were calculated [mean of differences between contacts / SD $_{(pooled)}$] [Vincent, 1995]. Pearson's correlation and co-efficients of determination were used to explore relationships between horizontal force characteristics during penultimate contact and peak knee abduction moments during the weight acceptance phase of final contact for normally distributed variables. Alternatively, Spearman's rank correlation was used if the data did not meet the assumption of normality.

Results

The mean ± *SD* approach velocities for cutting and pivoting were 4.40 ± 0.22 $m \cdot s^{-1}$ (95% Confidence Intervals [CI]: 4.31 – 4.50) and 4.03 ± 0.20 $m \cdot s^{-1}$ (95% CI: 3.95 – 4.11), respectively. Figure 2 shows time normalised force-time curves for penultimate and final contact for cutting and pivoting. Figures 3 and 4 show sagittal plane joint angles and moments for cutting and pivoting, respectively.

Differences between penultimate and final contact

Figure 2 shows clear differences between penultimate and final contact in terms of the magnitude of the peak vertical and horizontal forces and the absence of a vertical propulsive peak during the penultimate contact for both cutting (left) and pivoting (right) as the subjects' attempt to brake prior to final contact. During penultimate contact for cutting (Figure 3, left) and pivoting (Figure 3, right) the knee and hip joints flex throughout stance and the flexed position is maintained as the participants transition from penultimate to final contact, in order to help absorb the GRF's and prepare the body for an optimal position at final contact (i.e., lower centre of mass and allow the right leg to be planted out in front of the body). Conversely, during the final contact for cutting (Figure 3, left) marked joint flexion is observed for the first 40 to 60% of ground contact, whilst for pivoting all 3 joints flex to 40 to 80% of contact (Figure 3, right) before rapid extension of the joints during final contact of both tasks to propel the body into the re-acceleration phase of the task.

The joint moment profiles reveal a similar peak hip flexor moment during the weight acceptance phase (first 20 to 30% of contact) for both penultimate and final contact of the cut (Figure 4, top left), whereas peak knee moments occur around 30-40% of contact with slightly greater moments observed during penultimate compared to final contact (Figure 4, middle left). The penultimate contact for cutting shows a greater plantar flexion moment around 10% of contact, however, greater dorsi-flexor moments occur around 50% of final contact (Figure 4, left). The penultimate contact from the pivot reveals greater peak hip flexor, knee flexor and plantar flexor moments (10 to 20% of contact) compared to final contact (Figure 4, right), whereas final contact produces a second peak in hip, knee and ankle plantar flexor moments around 80% of contact.

Penultimate contact was significantly (P < 0.0001, ES = 1.27) shorter than final contact (0.192 ± 0.038 [95% CI: 0.176 – 0.208] s vs. 0.261 ± 0.045 [95% CI: 0.242 – 0.279] s) during cutting. With regard to the weight acceptance phase, Tables 1 shows that for cutting there were significantly greater ($P < .05$) peak horizontal braking forces, horizontal braking impulse, peak hip and knee flexion angles, and peak ankle plantar-flexor moments during the penultimate contact compared to final contact. In contrast, significantly ($P < .05$) greater average vertical and horizontal forces, average hip joint moments during weight acceptance were observed during final contact compared to penultimate (Table 1).

Penultimate contact was significantly (P < 0.0001, ES = 1.34) shorter than final contact (0.382 ± 0.068 [95% CI: 0.353 – 0.410] s vs. 0.517 ± 0.082 [95% CI: 0.483 – 0.551] s) during pivoting. During weight acceptance (Table 2), significantly greater ($P < 0.05$) normalised peak vertical and horizontal braking forces, peak knee flexion and ankle dorsi flexion angles, peak and average knee flexor moments and peak ankle plantar-flexor moments (Table 2) were observed during penultimate contact compared to final. However, final contact resulted in significantly ($P < 0.05$) greater average vertical and horizontal GRF, horizontal braking impulse and average hip joint moments during the weight acceptance phase (Table 2).

Relationships of horizontal force-time characteristics to peak knee abduction moments

Similar peak knee abduction moments (cut: 1.24 ± 0.47 [95% CI: 1.05 – 1.44] Nm·kg^{-1}; pivot: 1.17 ± 0.39 [95% CI: 1.00 – 1.33] Nm·kg^{-1}) were observed during the weight acceptance phase for both manoeuvres. Mean ± SD ratios between final and penultimate average horizontal forces for cutting and pivoting were 1.42 ± 0.22 and 1.81 ± 0.29, respectively. Mean ± SD ratios between final and penultimate horizontal braking impulses were 0.91 ± 0.20 and 1.14 ± 0.14 for cutting and pivoting, respectively. Among the above considered parameters only final/ penultimate average horizontal braking force ratio for pivoting was significantly related to peak knee abduction moments ($R = 0.466$, $R^2 = 22\%$, $P = 0.029$). However, for cutting, average horizontal braking force during penultimate contact was significantly related to peak knee abduction moments ($R = -0.569$, $R^2 = 32\%$, $P = 0.006$). No other horizontal force-time variables during penultimate contact was significantly (P > 0.05) related to peak knee abduction moments.

Discussion

The aim of the present study was to improve the understanding of braking strategy during cutting and pivoting by exploring kinematic and kinetic differences between penultimate and final contact of these actions in female soccer players. In addition, the study aimed to explore relationships between horizontal force-time characteristics during penultimate contact and the ratio of these variables between penultimate and final contact to peak knee abduction moments during the weight acceptance phase of final contact. The results revealed that for both cutting and pivoting the penultimate contact involved significantly shorter contact times, greater lower limb joint flexion, peak vertical and horizontal GRF's, but lower average vertical and horizontal GRF's compared to final contact. The penultimate contact for cutting involved significantly greater horizontal braking impulse, but the opposite was revealed for pivoting. Finally, only average horizontal braking force during penultimate contact was significantly related to peak knee abduction moments during cutting, whereas only a final/ penultimate average horizontal force ratio was significantly related to peak knee abduction moments during pivoting.

Differences between penultimate and final contact

A key finding of the present study was the observation that with both manoeuvres, significantly increased horizontal braking forces during the penultimate contact relative to the final contact were observed; substantiating our earlier pilot research on pivoting in male soccer players [Graham-Smith *et al*., 2009]. However, Graham-Smith *et al*., [2009] only examined peak forces and moments, whereas the present study evaluated the average across the weight acceptance phases and impulse. In contrast to achieving higher peak values during penultimate contact, when investigating average values the reverse was observed in that average vertical and horizontal forces were higher during final contact. Furthermore, due to the longer ground contact times during final contact of pivots a greater horizontal braking impulse was observed during pivoting, whereas for cutting horizontal braking impulse was significantly greater during penultimate contact. Taken together the results clearly illustrate that in the case of sharp cutting the penultimate contact plays a significant role in the braking strategy, whereas during pivoting due to the need to bring the horizontal velocity to zero before turning and accelerating back the other way more substantial braking action takes place during final contact.

The joint moment profiles illustrated similar findings to that for GRF's in that greater peak hip and knee flexor moments were observed during penultimate contact compared to final, but this was only significant for the pivot, substantiating previous research [Graham-Smith *et al.,* 2009]. When considering average hip flexor joint moments during the weight acceptance phase greater hip moments were observed during final contact for both manoeuvres owing to the fact that during weight acceptance for penultimate contact the initial hip flexor moment is immediately proceeded by an extensor moment, whereas a flexor moment persists for the final contact (Figure 4). The latter is perhaps due to differences in trunk movements that were observed between each footfall, in that during penultimate contact the players tended to lean back or were more upright throughout to increase braking, whereas during final contact the trunk tended to flex forward. This would have the effect of shifting the force vector more vertical due to the largest segment of the body shifting forwards and thus increasing the moment arm of the GRF vector relative to the hip joint.

Average knee flexor moments were greater (significant for pivoting) during penultimate contact compared to final contact for both manoeuvres. In contrast, both manoeuvres revealed greater ankle dorsi-flexor moments during final contact compared to penultimate. The latter was perhaps due to an initial forefoot plant during final contact evoking an ankle dorsi-flexor moment, whereas during penultimate contact an initial heel strike led to significantly greater initial ankle plantar flexor moments. Taken together these findings illustrate that the braking strategy for both manoeuvres in the sagittal plane has greater emphasis on counteracting knee flexor moments during penultimate contact, as opposed to hip flexor, knee flexor and ankle dorsi flexor moments during final contact.

Relationships of penultimate horizontal force-time characteristics to peak knee abduction moments during final contact

A key finding of the present study was that greater average horizontal forces during penultimate contact (R = -0.569) and that greater average horizontal forces relative to final contact (R = 0.466) were significantly related to lower peak knee abduction moments during final contact for cutting and pivoting, respectively. Previously, no significant relationships were found between final/ penultimate peak horizontal braking force ratios and peak knee abduction moments for cutting [Jones et al., 2015] or pivoting [Jones et al., 2016].

Previous studies investigating the optimal technique for injury prevention during cutting [Dempsey *et al*., 2007; Dempsey *et al*. 2009; McLean *et al.*, 2005; Sigward and Powers, 2007; Kristianlunds *et al*., 2014] have not considered the role of penultimate contact albeit often these studies consider a cutting angle of only 45°and thus, the results of this study suggest that for sharper changes of direction (i.e., > 45°) the kinematic and kinetics of penultimate contact should be considered to gather a greater understanding of optimal technique for injury prevention for both screening and technique training interventions. Furthermore, the results recommend increasing average horizontal forces during penultimate contact. One of the limitations of the study is that it is unknown what technical aspects are needed to increase average horizontal force during penultimate contact. Thus, future studies are required to gather a greater understanding of penultimate contact.

Due to the need of assessing velocity and total time to complete the tasks between subjects, it was beyond the scope of the study to explore the impact of increased braking during penultimate contact on performance. Theoretically, if a greater braking action can be achieved prior to final contact then less momentum has to be dissipated during the final contact, which may reduce final contact time that could impact on total time to complete the tasks (sum of total time into and out of the turn/ cut). For instance, Graham-Smith and Pearson [2005] have found that faster 180° turn times (5m approach and return time) were associated with lower contact times during the turn. Furthermore, Graham-Smith *et al*., [2009] found that faster total times to complete a pivot task similar to the present study were significantly related to greater horizontal braking forces (R^2 = 45%) and thus, the role of penultimate contact in terms of change of direction performance warrants further research.

A limitation of the present study is the pre-planned execution of each task as opposed to unanticipated, which has been shown to elevate knee joint loads during cutting [Besier *et al*., 2001]. Future studies need to examine whether the deceleration strategy identified in this study takes place in pre-planned situations only. A comparison between pre-planned and unanticipated situations in terms of the relationship between penultimate and final contact is needed. If such a strategy does not exist when the task becomes unanticipated, might suggest that enhancing players anticipatory or decision making skills could help modify technique and increase the braking action prior to final contact.

Finally, the results of the present study are based on changing direction tasks that involve much greater angles of direction change in comparison to the literature which often uses cutting angles of approximately 45° [Dempsey *et al*., 2007; Dempsey *et al*., 2009; McLean *et al*., 2005; Sigward & Powers, 2007]. It is likely that the role of penultimate contact may be less in such shallow angles of direction change, as there is less need to bring velocity to zero or close to zero before re-accelerating again. Therefore, a comparison between tasks (i.e., 45° cut *vs.* 90° cut *vs.* 180° pivot *vs.* 45° cross-cut) is required to evaluate the role of penultimate contact in different contexts. Furthermore, each task has been performed turning with the right limb, thus, it is unknown whether such strategies may differ between limbs. Thus, further research is required to investigate whether limb dominance influences the braking strategy during these manoeuvres.

To conclude, the present study revealed several significant differences in GRF's and lower limb joint angles and moments between penultimate and final contact of both cutting and pivoting, suggesting that the penultimate contact plays a role in braking and preparing the body for an optimal position for final contact in both manoeuvres. Furthermore, greater average horizontal forces during weight acceptance of the penultimate contact and greater average horizontal forces relative to final contact were significantly related to lower peak knee abduction moments during final contact for cutting and pivoting, respectively. This suggests that the penultimate contact may play a significant role in lowering knee joint loads during final contact where often ACL injuries occur. Future research into cutting and pivoting need to consider the penultimate contact to gain a better understanding of optimal technique for changing direction, in particular during unanticipated movements.

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Tables

Table 1. Mean ± SD (95% confidence intervals) force - time characteristics, joint angles and moment characteristics between the weight acceptance phase of penultimate and final contact for the 90° cut.

Variable	Penultimate contact			Final contact					
	Mean ± SD	95% CI LB	95% CI UB	Mean ± SD	95% CI LB	95% CI UB	$T_{(df)}$	P	ES
Force-time Characteristics									
Norm PK vertical (Fz) impact force (BW)	2.62 ± 0.31	2.49	2.75	2.69 ± 0.49	2.49	2.90	$-0.64_{(21)}$	0.529	0.18
AVE vertical (Fz) GRF during WA (BW)	1.09 ± 0.11	1.05	1.14	1.72 ± 0.21	1.63	1.81	$-14.653_{(21)}$	<0.0001	1.75
Norm PK horizontal (Fy) braking force (BW)	-1.57 ± 0.34	-1.42	-1.71	-1.37 ± 0.36	-1.22	-1.52	$-2.135_{(21)}$	0.045	0.54
AVE Horizontal (Fy) GRF during WA (BW)	-0.62 ± 0.11	-0.57	-0.66	-0.87 ± 0.15	-0.80	-0.93	$10.124_{(21)}$	<0.0001	1.38
Horizontal braking impulse (BW·s)	-0.12 ± 0.02	-0.11	-0.13	-0.10 ± 0.02	-0.10	-0.11	$-2.434_{(21)}$	0.024	0.61
Joint kinematics and kinetics									
PK hip flexion angle (°)	56 ± 15.6	50	63	48 ± 13.9	42	54	$2.591_{(21)}$	0.017	0.1
PK Hip flexor moment (Nm·kg^{-1})	2.83 ± 1.09	2.45	3.10	2.77 ± 0.77	2.37	3.28	$-0.188_{(21)}$	0.853	0.06
AVE hip moment during WA (Nm·kg^{-1})	-0.1 ± 0.5	-0.31	0.1	1.4 ± 0.7	1.04	1.66	$7.657_{(21)}$	<0.0001	1.51
PK knee flexion angle (°)	104 ± 9.1	100	107	62 ± 8.7	58	65	$17.924_{(21)}$	<0.0001	1.83
PK Knee flexor moment (Nm·kg^{-1})	3.19 ± 0.41	3.02	3.36	2.94 ± 0.36	2.79	3.09	$-2.052_{(21)}$	0.053	0.61
AVE knee moment during WA (Nm·kg^{-1})	1.8 ± 0.3	1.68	1.90	1.9 ± 0.4	1.74	2.08	$Z=-1.9155_{(21)}$	0.055	0.36

PK ankle dorsi flexion angle (°)	85 ± 9.3	81	89	87 ± 8.6	83	91	$-0.88_{(21)}$	0.389	0.02
PK Ankle plantar flexor moment (Nm·kg^{-1})	0.51 ± 0.21	0.42	0.60	0.33 ± 0.22	0.24	0.42	$4.586_{(21)}$	<0.0001	0.80
AVE ankle moment during WA (Nm·kg^{-1})	-0.4 ± 0.2	-0.31	-0.44	-0.8 ± 0.4	-0.68	-1.00	$5.83_{(21)}$	<0.0001	1.24

Key: SD = standard deviation, CI = confidence interval, LB = lower bound, UB = upper bound, ES = effect size, Norm = Normalised, PK = Peak, AVE = average, WA = weight acceptance.

Table 2. Mean ± SD (95% confidence intervals) force - time characteristics, joint angles and moment characteristics between the weight acceptance phase of penultimate and final contact for the 180° pivot.

Variable	**Penultimate contact**			**Final contact**					
	Mean ± SD	**95% CI LB**	**95% CI UB**	**Mean ± SD**	**95% CI LB**	**95% CI UB**	$\mathbf{T_{(df)}}$	**P**	**ES**
Force-time Characteristics									
Norm PK vertical (Fz) impact force (BW)	2.76 ± 0.49	2.56	2.97	2.46 ± 0.45	2.28	2.65	$2.819_{(21)}$	0.01	0.61
AVE vertical (Fz) GRF during WA (BW)	0.78 ± 0.06	0.75	0.81	1.33 ± 0.13	1.27	1.38	$-19.295_{(21)}$	<0.0001	1.85

Norm PK horizontal (Fy) braking force (BW)	-1.83 ± 0.28	-1.72	-1.95	-1.66 ± 0.30	-1.54	-1.79	$-2.519_{(21)}$	0.02	0.56
AVE Horizontal (Fy) GRF during WA (BW)	-0.5 ± 0.06	-0.48	-0.53	-0.9 ± 0.12	-0.86	-0.95	$15.692_{(21)}$	<0.0001	1.80
Horizontal braking impulse (BW·s)	-0.17 ± 0.01	-0.16	-0.17	-0.19 ± 0.02	-0.18	-0.20	$Z=-3.2999_{(21)}$	0.001	1.07
Joint kinematics and kinetics									
PK hip flexion angle (°)	77 ± 20.8	68	85	70 ± 14.6	64	76	$2.076_{(21)}$	0.05	0.09
PK Hip flexor moment (Nm·kg^{-1})	2.83 ± 0.66	2.56	3.11	2.56 ± 0.73	2.26	2.87	$1.556_{(21)}$	0.157	0.39
AVE hip moment during WA (Nm·kg^{-1})	-0.13 ± 0.33	-0.27	0.01	1.6 ± 0.5	1.39	1.81	$15.363_{(21)}$	<0.0001	1.78
PK knee flexion angle (°)	122 ± 7.3	119	125	69 ± 7.9	65	72	$35.893_{(21)}$	<0.0001	1.91
PK Knee flexor moment (Nm·kg^{-1})	3.05 ± 0.39	2.89	3.22	2.11 ± 0.33	1.98	2.25	$-14.760_{(21)}$	<0.0001	1.58
AVE knee moment during WA (Nm·kg^{-1})	1.47 ± 0.2	1.39	1.55	1.3 ± 0.3	1.20	1.47	$2.261_{(21)}$	0.035	0.50
PK ankle dorsi flexion angle (°)	87.3 ± 7.8	84	91	76 ± 10.8	71	81	$4.84_{(21)}$	<0.0001	0.14
PK Ankle plantar flexor moment (Nm·kg^{-1})	0.57 ± 0.18	0.49	0.64	0.22 ± 0.25	0.11	0.32	$8.334_{(21)}$	<0.0001	1.26
AVE ankle moment during WA (Nm·kg^{-1})	-0.17 ± 0.14	-0.11	-0.23	-0.8 ± 0.4	-0.62	-0.95	$7.369_{(21)}$	<0.0001	1.44

Key: SD = standard deviation, CI = confidence interval, LB = lower bound, UB = upper bound, ES = effect size, Norm = Normalised, PK = Peak, AVE = average, WA = weight acceptance.

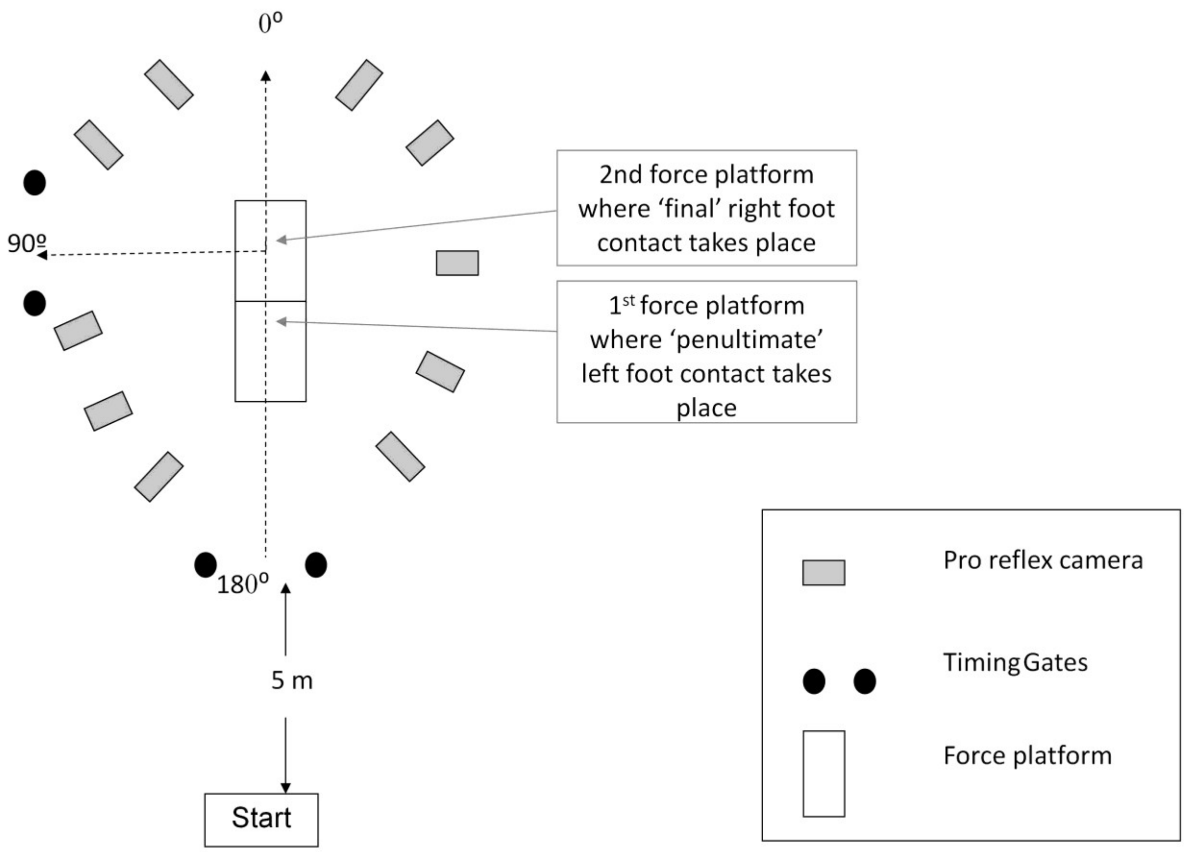
Figure Captions

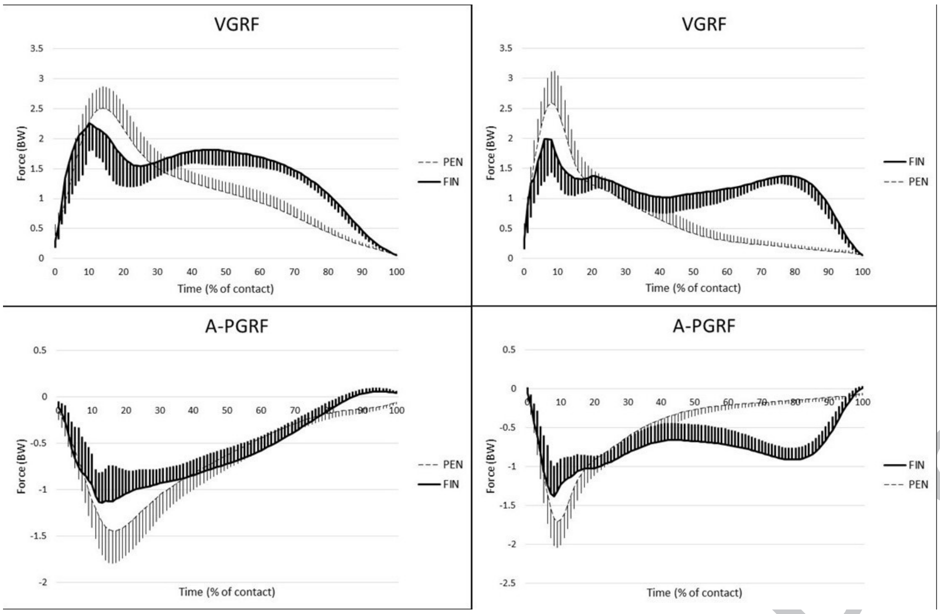
Figure 1. A plan view of the experimental set up.

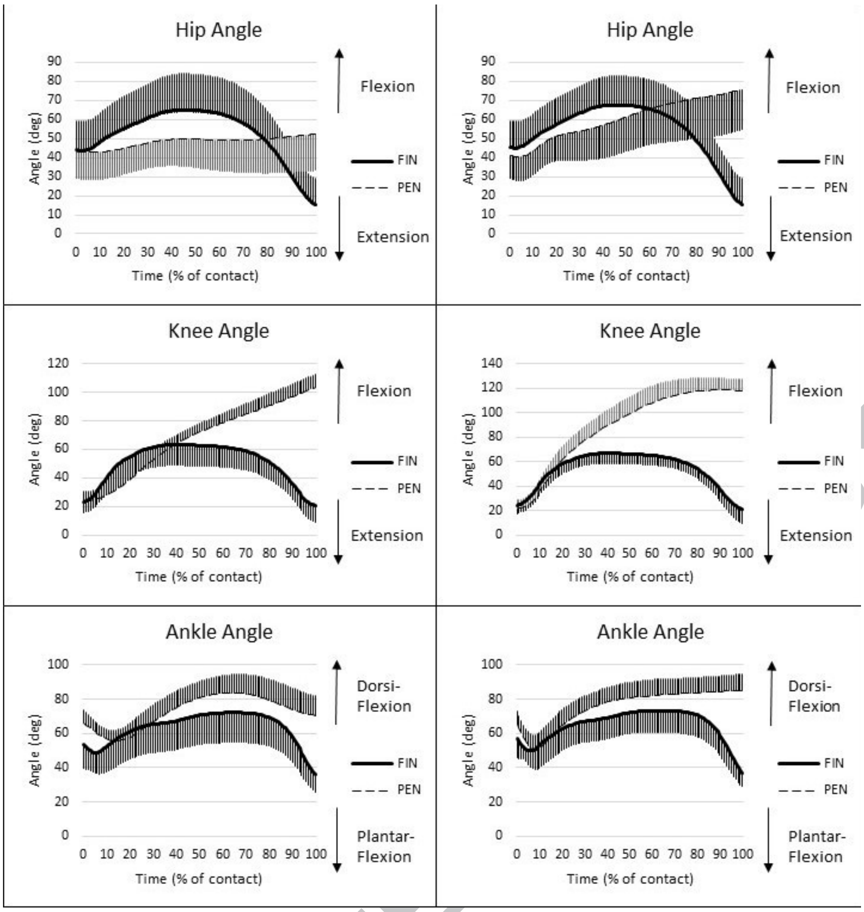
Figure 2. Ensemble averages for vertical (top) and horizontal (bottom) force time curves for cutting (left) and pivoting (right) during penultimate and final contacts during cutting (n=22).

Figure 3. Ensemble averages of normalised sagittal plane hip (top), knee (middle) and ankle (bottom) joint angles for cutting (left) and pivoting (right) during penultimate and final contacts of cutting. *SD* bars either +1 SD (bars above line) for that variable or – 1 *SD* (bars below line) for that variable (n=22).

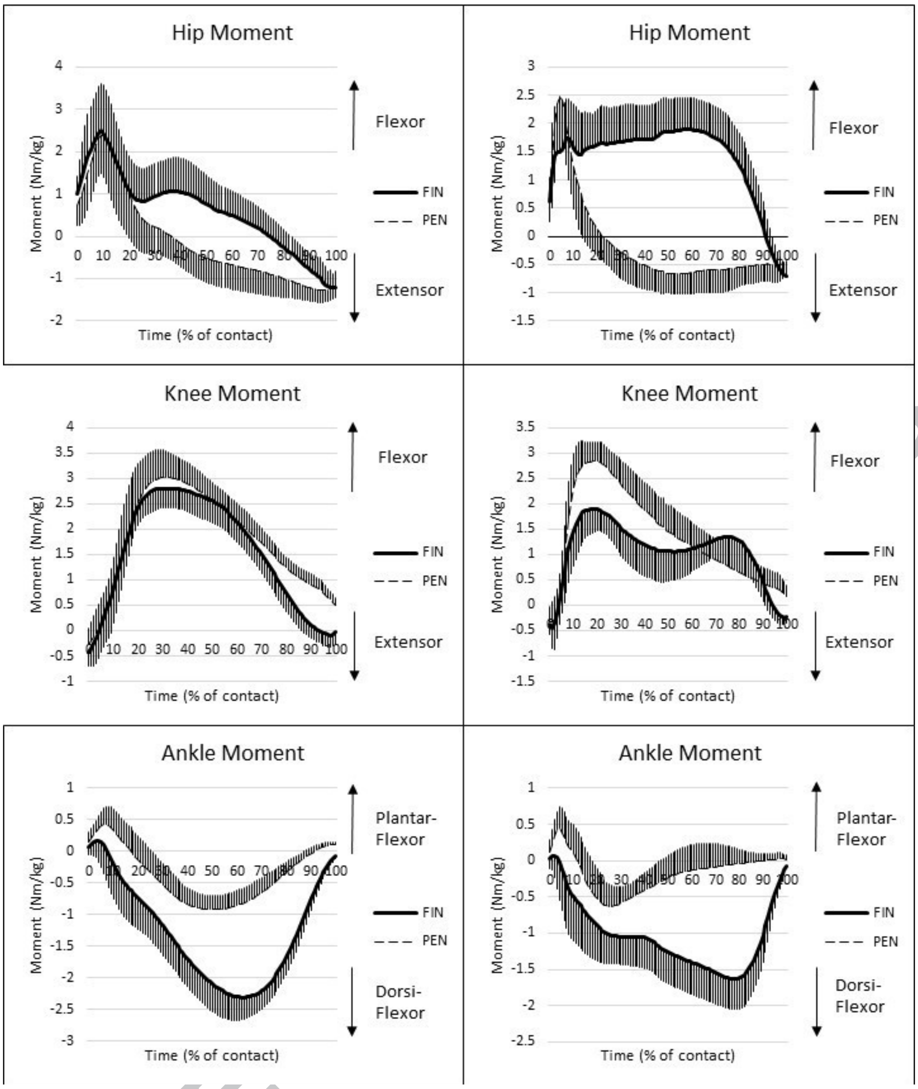
Figure 4. Ensemble averages of normalised sagittal plane external hip (top), knee (middle) and ankle (bottom) joint moments for cutting (left) and pivoting (right) during penultimate and final contact during cutting. SD bars either +1 *SD* (bars above line) for that variable or – 1 *SD* (bars below line) for that variable (n=22).


0º
90º
180º
5 m
Start
2nd force platform where 'final' right foot contact takes place
1st force platform where 'penultimate' left foot contact takes place
Pro reflex camera
Timing Gates
Force platform


VGRF
Force (BW)
Time (% of contact)
PEN
FIN
VGRF
Force (BW)
Time (% of contact)
FIN
PEN
A-PGRF
Force (BW)
Time (% of contact)
PEN
FIN
A-PGRF
Force (BW)
Time (% of contact)
FIN
PEN



Hip Angle
Angle (deg)
Time (% of contact)
Flexion
Extension
FIN
PEN
Hip Angle
Knee Angle
Knee Angle
Ankle Angle
Ankle Angle
Dorsi-Flexion
Plantar-Flexion



Hip Moment
Moment (Nm/kg)
Time (% of contact)
Flexor
Extensor
FIN
PEN
Hip Moment
Knee Moment
Knee Moment
Ankle Moment
Ankle Moment
Plantar-Flexor
Dorsi-Flexor

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