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ORIGINAL ARTICLE

Title:

Changes in leg kinematics in response to unpredictability in lateral jump execution

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Abstract

Lateral movements like cutting are essential in many team sport disciplines. The aim of the present study was to analyse adaptations in motor control in response to task unpredictability during lateral movement execution.

Twelve subjects performed lateral jumps with different landing modalities (stable, sliding or counteracting) that were either known (predictable setting) or unknown (unpredictable setting) prior to movement execution.

Results revealed that regardless of the landing modality, hip joint abduction was significantly greater in the unpredictable compared to predictable setting. Furthermore, during the sliding landing modality, hip flexion decreased from $211 \pm 7^\circ$ to $207 \pm 7^\circ$ and knee flexion decreased from $26 \pm 4^\circ$ to $24 \pm 4^\circ$ at the instant of ground contact in the unpredictable compared to predictable condition. During the stable landing modality, the knee joint abduction increased from $-0.3 \pm 6^\circ$ to $-3 \pm 6^\circ$ after initial ground contact in the unpredictable compared to predictable setting.

The present results support our hypothesis that pre-programmed motor activity depends on the predictability of the landing modality during lateral movements. According to its adaptation in the frontal plane and in some extent in the sagittal plane, the hip joint seems to play the major role in the modulation of the pre-programmed activity for successful lateral jump execution in an unpredictable setting. However, these kinematic adaptations are concerning since these changes were associated with higher knee abduction during the stable landing modality and therefore with possible higher risk of injury.

Key words

Lateral reactive jump, perturbation, feedforward motor control, knee injury

Introduction

Lateral movements, like side-stepping or cutting, play an important role in many sports. Performing these movements with high velocity and high accuracy is crucial for successful performance. It is therefore not surprising that higher skilled players demonstrate faster changes of direction than less skilled players and also display a better ability to perform more rapid changes of direction in response to a sport-specific stimulus (Gabbett & Benton, 2009). In addition to the performance aspect of lateral movements, these movements are also related to a relatively high risk of injuries, such as anterior cruciate ligament ruptures or ankle sprains (Alentorn-Geli et al., 2009; Fong et al., 2009; Olsen et al., 2004). Injuries experienced during lateral movements are often related to an unpredictable setting, e.g., perturbed landing due to being touched by an opponent or an insufficient shoe-surface traction.

To assess the motor control strategies that occur during lateral movements in more detail, it is reasonable to incorporate unpredictable experimental conditions when investigating cutting manoeuvres (Besier, Lloyd, Ackland, & Cochrane, 2001; Houck Duncan, & Haven, 2006; Rand & Ohtsuki, 2000) or forward jump landings (Borotikar, Newcomer, Koppes, & McLean, 2008; Brown, Palmieri-Smith, & McLean, 2009; Sell et al., 2006). In the studies dealing with a cutting task (e.g. Besier et al., 2001; Houck et al., 2006), unpredictability was achieved by triggering a direction board or a light stimulus during the inward approach to indicate the direction in which subjects had to perform their cutting manoeuvre. During unpredictable cutting, subjects had to adjust their motor control strategy according to the instruction they received from a light stimulus. Results revealed that knee joint loading was greater during the unpredictable condition and consequently, may have increased the risk of knee injuries (Besier et al., 2001; Sell et al., 2006). The reason for the higher joint loading in the unpredictable condition may be that there was not enough time for individuals to pre-program an appropriate level of muscular

activity when the cutting direction cannot be anticipated. This assumption is based on previous work examining vertical drop jumps (Leukel, Taube, Lorch, & Gollhofer, 2012). In this study, uncertainty was introduced by instructing subjects to switch to a landing movement upon an auditory cue, which was sometimes elicited prior to touch-down. Despite both drop jump conditions being mechanically identical, introducing uncertainty in task execution resulted in an altered muscular pre-activation pattern due to modifications in pre-programmed motor commands. The influence of unpredictability in the task execution has also been investigated during walking, where unpredictable settings like slipping (Marigold & Patla, 2002; Oates, Frank, & Patla, 2010) or tilting surfaces (Nieuwenhuijzen & Duysens, 2007) were introduced.

Pre-programmed or feedforward motor control refers to neuromuscular activity being planned and executed based on sensory information that is available prior to movement execution. In contrast, during reactive (feedback) motor control, sensory feedback is used ‘online’ to guide and correct movements while performing the motor task (Bastian, 2006; Taube, Leukel, & Gollhofer, 2012). In the current study, we were interested in i) how task unpredictability about the landing modality influenced lateral movement execution and more specifically, ii) how feedforward motor control is adapted in lateral jumps to counteract this unpredictability. This is important because unpredictability during lateral movements closely resembles daily and sport activities, when pre-programmed commands may need to be changed due to unexpected events (e.g. unstable/slippery surface).

The aim of the present study was to investigate changes in leg kinematics due to task unpredictability during lateral reactive jumps. Based on Leukel et al. (2012), we firstly hypothesized that leg kinematics would be different in the unpredictable compared to the predictable setting, due to adaptations of the feedforward motor control. Secondly, Fleischmann, Gehring, Mornieux, and Gollhofer (2010) have reported that knee and hip joints

rather than the ankle joint play a major role in the execution of lateral reactive jumps. Accordingly, we further hypothesized that leg kinematics will be primarily modulated at the knee and hip joints in order to compensate for task unpredictability.

Materials and methods

Subjects

Twelve physically active volunteers (five females and seven males; age: 24 ± 2 years; height: 171 ± 10 cm; mass: 70 ± 11 kg) participated in the study. Prior to testing, all subjects were informed about possible risks and gave written informed consent. All procedures were approved by the local ethics committee.

Protocol

From a standing position, subjects performed a lateral reactive movement by jumping 120 cm to their right side and then pushing off with their right leg to get back to their original position. This dynamic lateral jump technique has been described in detail by Fleischmann et al., (2010). During landing, subjects were instructed to place their foot perpendicular to the jumping direction with a tolerance of $\pm 5^\circ$ rotation. This ensured inter-subject homogeneity during the execution of the lateral jump, as foot rotation can influence the biomechanics of the lower limbs (Fleischmann et al., 2010).

In order to induce lateral perturbations, subjects performed the lateral jump on a motor-driven plate, which could translate in the horizontal (medio-lateral) direction (Figure 1). The lateral jump was performed under three different landing modalities, either without any perturbation (stable condition), or with an initial perturbation to the right (sliding condition) or to the left

(counteracting condition). For the two landing modalities involving a perturbation, the motor-driven plate started to move as soon as the foot made initial contact with the plate. Each perturbation consisted of a 10 cm translation in either direction, which took place within 200 ms and resulted in a maximal plate velocity of 0.54 m.s^{-1} after 60 ms.

Unpredictability was introduced using these three different landing modalities (stable, sliding, counteracting) that were either known (predictable setting) or unknown (unpredictable setting) prior to movement execution. Comparing mechanically identical landing modalities in a predictable and unpredictable setting allows for the assessment of alterations in the feedforward motor control during lateral jumping. Subjects either started with lateral jumps in the ‘predictable setting’, where they knew prior to the initiation of the jump which of the three landing modalities would occur, or they started the lateral jumps without this knowledge (unpredictable setting). The order of predictable and unpredictable settings was randomly assigned over the twelve subjects. Prior to the measurements, participants were given enough practice trials, so that they felt comfortable with all landing modalities, with both predictable and unpredictable settings. All subjects performed the lateral jumps while wearing a neutral sport shoe without any specific technology or damping material (Adidas Samba, Adidas, Herzogenaurach, Germany).

Material

The specially designed motor-driven plate (University of Sport Science, Freiburg, Germany) constituted of two independently moving plates (1.15 m x 0.3 m), each driven by a separate motor (AKM51G, Danaher Motion, Dusseldorf, Germany). The main characteristics for each motor were as follows: power up to 1200 Watts; 4.75 N.m torque; 5000 rotations per minute motor speed; 400 N lateral force. The 0.2 m height motor-driven plate required a wood construction around the device to get a large surface (2.75 m x 1.4 m) at this height, allowing

subjects to feel comfortable while performing the lateral jumps. For the purpose of the study, both plates were simultaneously controlled resulting in a landing surface of 0.55 m x 0.6 m in size. The plates were triggered using a light barrier (Optojump, Microgate S.r.l., Bolzano, Italy) that was placed 2 cm above the landing surface. This height compensated for the delay of the motor-driven plate and ensured that movement of the plates would be initiated at initial foot contact.

Three-dimensional leg kinematics were recorded using 14 reflective skin markers (\varnothing 14mm) placed with self-adhesive tape on anatomical landmarks of the subjects' pelvis and right leg. Specifically, markers were placed on the anterior superior iliac spines, the posterior superior iliac spines, the great trochanter, medial and lateral epicondyle of the knee, the tibia (two markers), the medial and lateral malleolus, and on the posterior, medial and lateral aspects of the heel cup. An additional marker was placed on the first metatarsal head to detect foot contact with the ground. This marker placement was based on a previously published article focusing on the lower limb during such lateral reactive jumps (Fleischmann et al., 2010). Markers were captured with a 12-camera motion analysis system (Vicon V-MX, VICON Motion Systems Ltd., Oxford, UK) with a sampling frequency of 200 Hz. A static trial with the subject standing in a pre-defined neutral position was used to define the kinematic model and to calculate segment lengths and joint centres (Grood & Suntay, 1983; Wu et al., 2002). The kinematic modelling was performed with the motion analysis software (Vicon Nexus 1.6.1, VICON Motion Systems Ltd., Oxford, UK). Joint kinematics in three rotational degrees of freedom were determined using an yxz Euler rotation sequence of the respective segment coordinate system according to the global reference system defined in Vicon. This yielded a rotation sequence around the flexion/extension axis first, then around the abduction/adduction axis followed by the rotation around the external/internal axis. Before calculating the joint

kinematics, data were smoothed with a spline filter (Woltring filter; mean square error = 10 mm²).

Data analysis

Kinematic data for the ankle, knee and hip joints in the sagittal (positive values dorsiflexion, knee flexion, hip flexion) and frontal (positive values for ankle inversion, knee adduction, hip abduction) planes were analysed. Comparison of mechanically identical landing modalities (e.g. stable landing in the predictable setting vs. stable landing in the unpredictable setting) served to identify differences in the feedforward motor control strategy. Kinematic parameters were investigated at the time of the initial contact (IC) with the ground and at 140 ms after initial touchdown as it was previously proposed that this time reflects the end of the reflex induced activity (Fleischmann et al., 2010). Data obtained at this later instant gave further information about the consequences of changes in the feedforward motor control adaptation. IC and toe-off were determined based on the first metatarsal marker's vertical acceleration signal. At these two time points, peak acceleration values were detected and contact time could be determined. This method, adapted from an algorithm proposed for running (Maiwald, Sterzing, Mayer & Milani, 2009) yielded contact times that were similar to values obtained from the vertical ground reaction force signal, when lateral reactive jumps were performed on a force plate during pilot measurements. The foot progression angle was defined as the rotation of the calcaneus, defined by the 3 markers placed on the heel cup, with respect to the global coordinate system. The measurement of the foot progression angle was used to exclude all trials where the foot was not perpendicular ($90 \pm 5^\circ$) to the jump direction at IC.

Statistics

The selected kinematic parameters were averaged across six trials for each subject in each condition and served as the basis for the statistical analysis. After having confirmed that the

data followed a normal distribution (Kolmogorov-Smirnov test), the influence of task predictability (predictable vs. unpredictable setting) on the dependent kinematic variables was analysed using a variance analysis (General Linear Model) with 2 factors (task predictability x landing modality) with repeated measures. According to the aim of the study, the main effect at the level of the task predictability was primarily analysed. In case of an interaction effect, a Newman-Keuls post-hoc test was used to identify where these significances lay. The level of significance was set at 0.05.

Additionally, effect sizes were reported by means of the Cohen's d_z value, each time the interaction effect was significant. Effect size values (d_z) below 0.5 were considered as small, values between 0.5-0.8 were interpreted as medium while values above 0.8 showed a large effect.

All results are presented as group means \pm standard deviations (SD).

Results

Contact time

The contact time during the different lateral jump conditions is depicted in Figure 2. Statistical analysis revealed no significant influence of task predictability for each of the three landing modalities.

Leg kinematics at IC

As shown in Table I, lower limb kinematics were influenced by task predictability. At IC, hip joint abduction was significantly affected by the task predictability ($P < 0.001$). A detailed analysis of the interaction effect ($P = 0.002$) revealed that values for the stable ($P < 0.001$; $d_z = 2.01$), sliding ($P = 0.002$; $d_z = 0.70$) and counteracting ($P = 0.001$; $d_z = 0.81$) conditions were

all significantly greater in the unpredictable setting. Although the task predictability did not show any significant main effect on the hip and knee flexion, the interaction effect pointed out significantly smaller hip flexion ($P = 0.047$; $dz = 1.78$) and knee flexion ($P = 0.003$; $dz = 0.83$) values during the sliding landing modality in the unpredictable compared to the predictable setting. Knee adduction and kinematics of the ankle joint were not affected by changes in task predictability and no interaction effect was observed.

Leg kinematics 140 ms after IC

Kinematic variables assessed 140 ms after IC are reported in Table II. Again, hip joint abduction was significantly greater in the unpredictable compared to the predictable setting ($P < 0.001$). The analysis of the interaction effect ($P = 0.001$) revealed that all landing modalities were significantly influence by the task predictability, i.e. for the stable ($P < 0.001$; $dz = 2.33$), sliding ($P = 0.001$; $dz = 0.65$) and counteracting ($P < 0.001$; $dz = 1.12$) conditions.

As previously seen at IC, task predictability did not show any significant main effect on the hip and knee flexion, but the interaction effect was significant ($P = 0.001$ and $P < 0.001$, respectively). When compared to the predictable setting, unpredictability led to less hip flexion in the stable ($P = 0.001$; $dz = 0.97$) and the sliding landing modalities ($P = 0.011$; $dz = 1.13$). Furthermore, in the unpredictable setting, knee flexion was significantly smaller in the stable ($P = 0.004$; $dz = 0.66$) and sliding ($P < 0.001$; $dz = 1.16$) modalities, but greater in the counteracting landing modality ($P = 0.035$; $dz = 0.85$) compared to the predictable setting.

Additionally, knee abduction was significantly influenced by the task predictability 140 ms after IC ($P = 0.006$). Moreover, the interaction effect ($P = 0.016$) revealed that this was due to greater knee abduction during the stable landing modality ($P < 0.001$; $dz = 1.16$). Finally, the ankle flexion was significantly different between predictable and unpredictable settings ($P = 0.039$). Despite no main effect but due to the interaction effect ($P < 0.001$), larger ankle

inversion was observed in the stable landing modality ($P = 0.004$; $dz = 0.86$) but a smaller amount of ankle inversion was found during the counteracting modality ($P = 0.007$; $dz = 1.09$).

Discussion

Although different types of lateral movements have recently been studied (Borotikar et al., 2008; Brown et al., 2009; Fleischmann et al., 2010; Nigg, Stefanyshyn, Rozitis, & Mundermann, 2009), this is the first time that task unpredictability about the landing modality has been examined by combining a decision-making paradigm with varying perturbations upon landing. This protocol enabled the assessment of how feedforward motor control processes alter the kinematics of lateral jumping. The primary finding of the present study was that leg kinematics was modified during lateral reactive jumps when subjects did not know in advance how the landing surface would react. More specifically, when subjects were uncertain about the behaviour of the landing surface, hip abduction was greater while both knee and hip flexion were reduced at initial foot contact during the sliding landing modality, which is a very common perturbation, since it results from a loss of grip.

The unaltered kinematic values observed at initial foot contact during the unpredictable setting indicated that subjects could not anticipate the landing modality (stable, sliding or counteracting) and consequently, were unable to pre-adjust their leg kinematics accordingly. Moreover the data are consistent with previous observations using different study designs showing that as soon as task unpredictability is enhanced, changes in leg kinematics occur (Besier et al., 2001; Sell et al., 2006). These changes may be the result of having insufficient time to pre-program a task-specific leg kinematic strategy.

In the unpredictable compared to predictable setting, subjects increased their hip joint abduction and during the sliding landing modality, reduced their knee and hip flexion at IC. This underlines how the feedforward motor control system adapted leg kinematics to compensate for task unpredictability. Since this compensation was most consistently (i.e., across all three landing modalities) observed at the hip joint, the findings strengthen the argument that the hip joint plays a crucial role for the successful execution of lateral reactive jumps (Fleischmann et al., 2010).

Differences in the sagittal plane hip and knee joint angles were only observed during the sliding landing modality. It can be argued that the pre-programmed motor activity in the unpredictable setting was made most appropriate for the counteracting modality. This makes sense as the counteracting landing modality was probably the most challenging. However, it is likely that this pre-programmed motor activity was not appropriately adjusted for the other landing modalities and as a result, yielded significant kinematic differences in the sliding modality. This observation differs slightly from previous findings, where it was demonstrated that when subjects had to alter their movement execution (from rebounding to landing or vice versa) based on external cues, they chose an intermediate activation pattern lying in-between the two possible movements (Leukel et al., 2012). This intermediate activity pattern allowed subjects to fulfil both tasks. In contrast, subjects in the present study did not choose an intermediate motor activity pattern, as this might have been unsuitable for all landing modalities, especially the counteracting one.

Changes in leg kinematics due to the unpredictable setting were not only limited to initial contact, but continued to have consequences 140ms after ground contact. Hip abduction was still greater while hip flexion was smaller in both the stable and the sliding landing modalities. Additionally, there was significantly greater knee abduction in the stable landing modality at this time (3.0° vs. 0.3° for predictable and unpredictable settings, respectively). The knee joint

was also more extended in the sliding landing modality, but remained more flexed during the counteracting modality in the unpredictable setting. Therefore, knee flexion was not only less constant over the different landing modalities in the unpredictable setting but also more extended when sliding. This finding can be interpreted as a poor compensation as decreased knee flexion has been identified as a risk factor for knee injury, i.e. anterior cruciate ligament rupture (McLean, Lipfert, & Van den Bogert, 2004). Together with increased knee abduction, this indicates a poorer joint control 140 ms after IC in the unpredictable setting.

At the ankle joint, no significant differences in joint angle were identified at the time of IC. However, 140 ms after IC, less constant ankle inversion could be observed across all three landing modalities in the unpredictable setting (angle range across landing modalities of 4.4° vs. 7.4° for predictable and unpredictable conditions, respectively). Moreover, the larger ankle inversion in the stable landing modality of the unpredictable setting (20.5° vs. 18.6°) could be associated with higher ankle injury risks (Fong et al., 2009). This data, in conjunction with the previously discussed events at the knee, reflects a poorer control of the lower limb joints 140 ms after IC in the unpredictable compared to the predictable setting. Furthermore it is worth noting that this inadequate control of the lower limb after 140 ms is specifically taking place during the stable landing modality. Thus, an unsuitable feedforward motor control strategy can still have consequences to lateral jumping when no surface perturbation is presented.

The current results suggest that movement control during unpredictable conditions is less organized and less adapted to account for the specific requirements of the task. Conversely, if the individual can anticipate what will happen in advance, adequate pre-programmed activity ensures an optimal execution of lateral reactive jumps. Thus, pre-programmed, feedforward activity likely plays an important role in preventing the lower limb, and especially the knee joint, from possible injuries. Indeed, different studies suggested that greater knee abduction and

smaller knee flexion increase the anterior cruciate ligament injury risk (Hewett et al., 2005; McLean et al. 2004; Myer, Ford, & Hewett, 2011). Furthermore, it has been shown that hip angular displacement in the frontal plane can influence knee joint abduction (Hewett & Myer, 2011; Imwalle, Myer, Ford, & Hewett, 2009). As lateral reactive jumps are exclusively performed in the frontal plane, hip joint abduction at IC is substantially larger than during cutting manoeuvres or landings (Hewett & Myer, 2011; Imwalle et al., 2009). As this greater hip joint abduction could lead to a larger external abduction moment, this would also increase the knee joint abduction moment (Hewett & Myer, 2011). Indeed, this association has been reported by Sigward & Powers (2007) in a study comparing female athletes with normal and excessive knee joint abduction moment while performing cutting maneuvers.

While the present study design enabled to investigate feedforward motor control strategy during lateral movements, future studies should include electromyography measurements to determine if observed leg kinematic adaptations in an unpredictable setting are related to different neuromuscular strategies. Another limitation of the present study might be the lack of kinetic data to further support the discussion dealing with the injury risk issue. Further studies should try to implement a moving force plate to analyse kinetics during perturbed landings.

In conclusion, pre-programmed motor control was most successful in a predictable setting allowing a 'safe' lateral movement. As soon as the landing modality became unpredictable, subjects adjusted their pre-programmed motor activity by primarily increasing the hip abduction. This strategy could not prevent unsuitable lower limb configurations, especially at the knee joint, for all landing modalities and thus, may have the potential for an increased risk of injury. This finding was unexpected as it was assumed that subjects would display a safety strategy that encompasses all potential landing modalities (stable, counteracting and sliding)

without any risk. Lateral movements may be too complex to allow such a general safety strategy when performed in an unpredictable setting.

The present results should be considered when conceptualizing training interventions. Confronting athletes with task unpredictability about the landing surface and the potential for a slip during training may better prepare them to successfully encounter such situations during games and thus, may be useful for injury prevention. Indeed, improving game-specific motor control has been shown to reduce the injury risk (Renstrom et al., 2008).

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Figure Captions

Figure 1. Schematic view of the lateral reactive jump on the motor-driven plate. During the sliding landing modality, the plate moved to the right (i.e., away from the subject), while during the counteracting landing modality, the plate moved to the left.

Figure 2. Mean \pm SD values of the contact time (ms) for the three different lateral reactive jump landing modalities in the predictable (black bars) and unpredictable setting (white bars).

Table I. Mean \pm SD values of the different kinematic dependent variables at the instant of initial contact for the three different lateral reactive jump landing modalities in the predictable and unpredictable settings.

The significance of the main effect for the task predictability is indicated by the *P* value or is reported as non significant (NS).

*: indicates that values in the unpredictable setting are significantly different from the predictable setting in the same landing modality in case of a significant interaction effect.

Table II. Mean \pm SD values of the different kinematic dependent variables 140 ms after initial contact for the three different lateral reactive jump landing modalities in the predictable and unpredictable settings.

The significance of the main effect for the task predictability is indicated by the *P* value or is reported as non significant (NS).

*: indicates that values in the unpredictable setting are significantly different from the predictable setting in the same landing modality in case of a significant interaction effect.

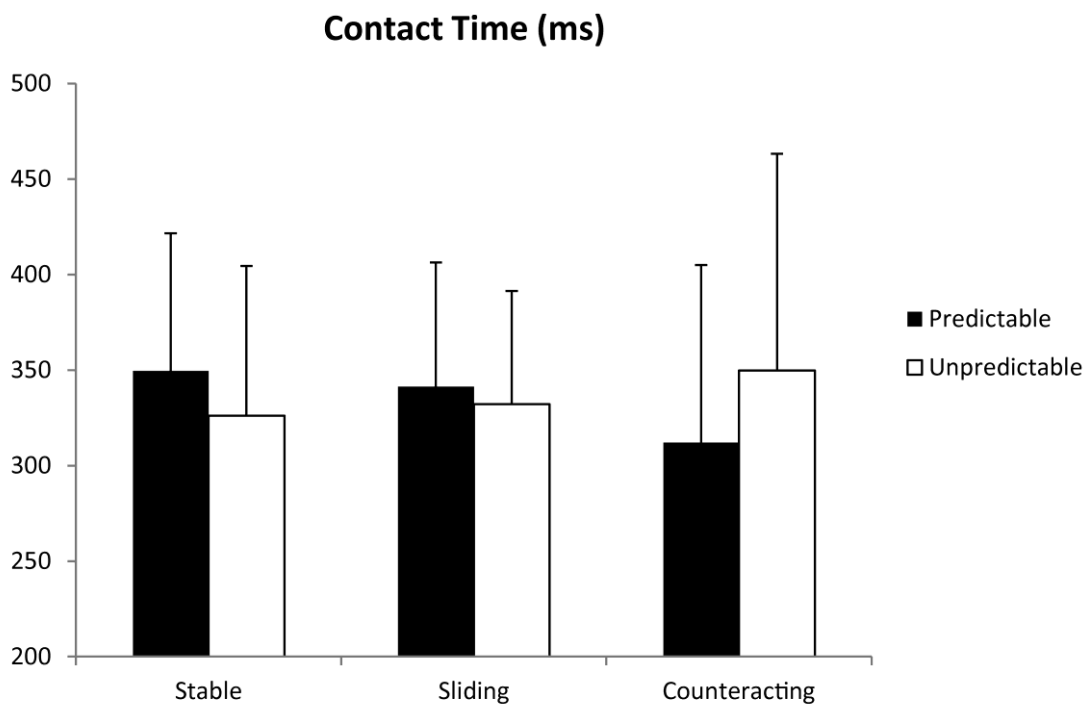
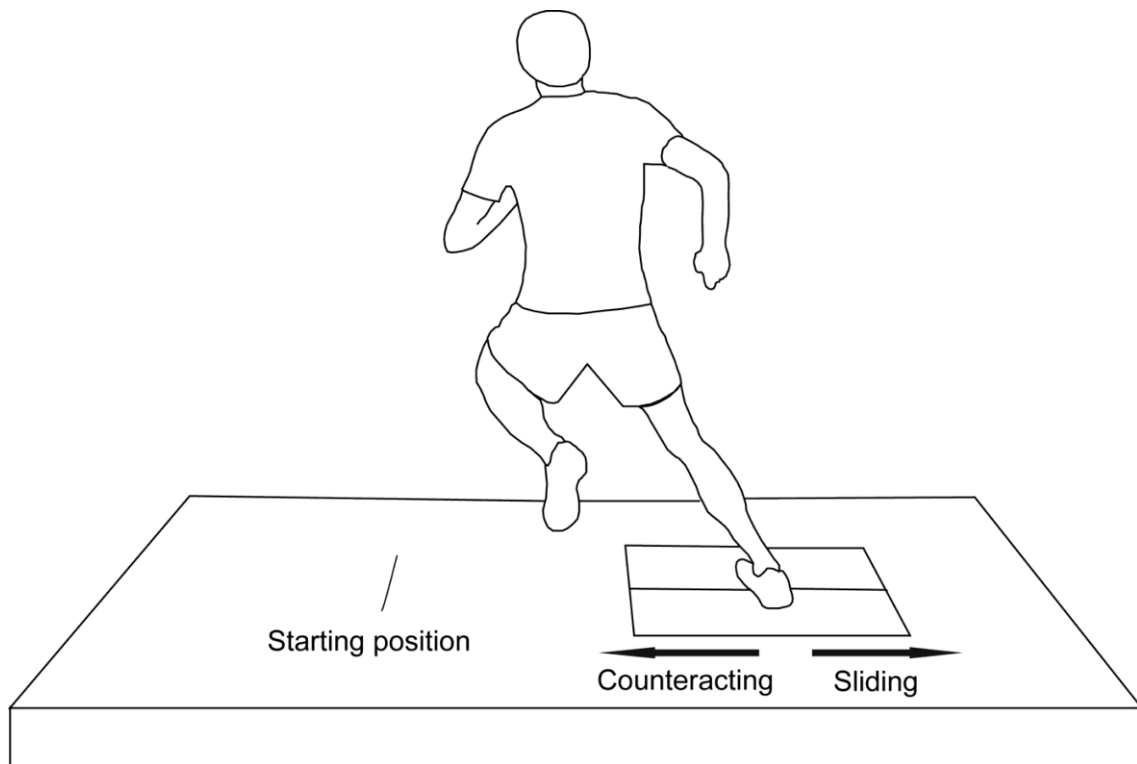


Table I. Leg kinematics at IC

	Predictable Setting			Unpredictable Setting			main effect (<i>P</i> value)
	Stable	Sliding	Counteracting	Stable	Sliding	Counteracting	
Hip Flexion (°)	29.9±6.5	30.6±7.2	26.1±10.1	26.6±8.2	27.4±7.2 *	27.2±7.5	NS
Hip Abduction (°)	26.4±7.3	28.4±6.8	28.6±6.4	31.0±6.1 *	30.4±5.8 *	30.7±6.1 *	<0.001
Knee Flexion (°)	23.6±5	26±3.5	23.3±3.8	23.7±4	24±3.7 *	23.8±3.7	NS
Knee Adduction (°)	-1.1±3.9	-1.5±4.3	-1.3±3.8	-1.7±4.4	-1.6±4.5	-1.3±4.4	NS
Dorsiflexion (°)	-13±8.9	-8.7±8.8	-11.3±8.6	-12.8±6.1	-13.8±8.1	-13.1±7.3	NS
Ankle Inversion (°)	12.4±5.5	11.6±5.1	10.8±4.9	10.4±3.6	9.8±4	10.4±4	NS

Table II. Leg kinematics 140ms after IC

	Predictable Setting			Unpredictable Setting			main effect (<i>P</i> value)
	Stable	Sliding	Counteracting	Stable	Sliding	Counteracting	
Hip Flexion (°)	40.8±5.8	37.8±6.5	36.3±9.8	34.9±9.6 *	32.2±9.3 *	39.0±8.7	NS
Hip Abduction (°)	23.8±8.1	31.1±7.1	24.5±7	31.4±6.6 *	33.3±6.3 *	27.9±6.5 *	<0.001
Knee Flexion (°)	50.4±3.9	46.7±3.2	50.1±5.6	46.8±6.5 *	41±6 *	52.8±5.5 *	NS
Knee Adduction (°)	-0.3±6.2	-2.6±6.3	-0.9±6.3	-3±6 *	-3.1±5.9	-1.9±6.3	=0.006
Dorsiflexion (°)	17.5±7.1	17±8.9	19.8±8.6	17±8.2	12.5±8.5	19.5±7.4	=0.039
Ankle Inversion (°)	18.6±4.3	22.3±4.7	17.9±4.1	20.5±5.1 *	23.5±5.7	16.1±4.5 *	NS