Effects of treadmill versus overground soccer match simulations on biomechanical markers of anterior cruciate ligament injury risk in side cutting

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Abstract

This study aimed to investigate whether treadmill versus overground soccer match simulations have similar effects on knee joint mechanics during side cutting. Nineteen male recreational soccer players completed a 45 min treadmill and overground match simulation. Heart rate (HR) and rating of perceived exertion (RPE) were recorded every 5 min. Prior to exercise (time 0 min), at 'half-time' (time 45 min) and 15 min post exercise (time 60 min) participants performed five trials of 45° side cutting manoeuvres. Knee abduction moments and knee extension angles were analysed using two-way repeated measures ANOVA ($\alpha = 0.05$). Physiological responses were significantly greater during the overground (HR 160 ± 7 beats · min^{-1}; RPE 15 ± 2) than treadmill simulation (HR 142 ± 5 beats · min^{-1}; RPE 12 ± 2). Knee extension angles significantly increased over time and were more extended at time 60 min compared with time 0 min and time 45 min. No significant differences in knee abduction moments were observed. Although knee abduction moments were not altered over time during both simulations, passive rest during half-time induced changes in knee angles that may have implications for ACL injury risk.

Keywords: Knee mechanics, anterior cruciate ligament, soccer

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Introduction

Anterior cruciate ligament (ACL) injuries have a high prevalence in soccer with incidence rates of between 0.6 and 8.5% in male players, regardless of their playing level (Walden, Hagglund, Werner, & Ekstrand, 2011). This has multiple negative health concerns, including early onset of osteoarthritis, damage to knee menisci and chondral surfaces, and decreased activity levels due to functional instability (Yu & Garrett, 2007).

The majority of ACL injuries take place during non-contact utility movements such as running, jumping, landing, or suddenly changing direction (e.g. side cutting), rather than whilst interacting with other players (Fauno & Wulff Jakobsen, 2006; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). The side cutting manoeuvre requires a sudden deceleration upon impact with the ground, accompanied by a rapid change in direction (McLean, Lipfert, & van den Bogert, 2004). Studies have shown that during the weight acceptance phase of side cutting, which is from the initial foot contact to the first trough in the vertical ground reaction force (Dempsey et al., 2007), peak abduction knee moments are up to two times higher than those observed during straight line running indicating that this may be the period of high ACL strain (Besier, Lloyd, Cochrane, & Ackland, 2001). When the peak abduction moments are coupled with anterior tibial translations, ACL strain is significantly higher (Withrow, Huston, Wojtys, & Ashton-Miller, 2008). An extended knee position at initial contact during side cutting has also been associated with increased ACL strain, and with increased anterior tibial shear force due to an increased patellar tendon-tibia shaft angle (Hughes & Watkins, 2006; Laughlin et al., 2011; Yu, Lin, & Garrett, 2006).

In soccer matches, the rate of injuries increases with match duration. Hawkins et al., (2001) have demonstrated that a large percentage of non-contact injuries occur in the last 15 min of the first half and in the last 15 min of the second half of soccer matches. Furthermore, consistent with an increased injury rate with match duration, decreases in distance covered and high-intensity running have been observed (Bangsbo, Norregaard, & Thorso, 1991; Mohr, Krustrup, & Bangsbo, 2003). Together, these findings lead to a speculation that exertion induced by match duration may contribute to injury related to decreased muscle strength (Delextrat, Gregory, & Cohen, 2010; Greig, 2008; Small, McNaughton, Greig, & Lovell, 2010) and altered movement mechanics (Greig, 2009; Sanna & O'Connor, 2008; Small, McNaughton, Greig, Lohkamp, & Lovell, 2009).

Numerous studies have reported that high levels of exertion induced by a short duration high intensity exercise can alter lower extremity mechanics during side cutting manoeuvres. Tsai, Sigward, Pollard, Fletcher, and Powers (2009) observed an increase in the peak knee abduction moments (peak external knee abduction moments) as well as peak knee internal rotation angles in anticipated side cutting after high intensity consecutive repetitions of vertical jumps and short sprints. In addition, Lucci, Cortes, Van Lunen, Ringleb, and Onate (2011) reported an increased knee extension angle at initial contact and decreased knee internal rotation in unanticipated side cutting after short duration and high intensity exercises consisting of a series of step-up and down movements, vertical jumps, and agility drills. However, the high intensity and short duration exercises used in both studies do not represent the level of exertion and activity profile as occurs during a soccer match.

The studies by Greig (2009) and, Sanna and O'Connor (2008) are perhaps the closest attempts to investigate the effect of soccer match exertion on knee joint mechanics. Greig (2009) conducted 90 min soccer match simulations with a motorised treadmill to replicate the activity profile of soccer match-play (Bangsbo, 1994) and observed a more extended knee at initial contact after 45 and 90 min, and after the half-time interval. The treadmill match simulation was designed to represent the mechanical demands of the intermittent running characteristics of soccer, replicating the short duration of exercise bouts, and subsequently providing a valid frequency of speed change (Greig, 2009). Furthermore, Sanna and O'Connor (2008) used a 60 min overground soccer match simulation and found that this elicited significant pre- to post differences in knee internal rotation angles but found no changes in peak knee abduction moments and knee extension angles during anticipated side-cutting. Their overground simulation consisted of straight-line shuttle runs at various speeds between two cones positioned 20 m apart. The disparity in protocols may be a reason for the dissimilar findings between these studies. Although both simulations have represented either the mechanical (Greig, 2009) or physiological (Sanna & O'Connor, 2008) demands of soccer match-play, neither incorporated multidirectional utility movements. Overground simulations, incorporating multidirectional utility movements, may offer the greatest external validity for actual match-play and for the investigation of knee injury biomechanics. At present, whether any treadmill or overground simulations can accurately recreate soccer match-play and influence mechanical loading remains unknown.

The present study aimed to compare the effects of match exertion induced by treadmill and overground soccer match simulations on knee mechanics during side cutting. The null hypothesis was that there would be no differences in peak knee abduction moments at weight acceptance phase and knee extension angles at initial contact during side cutting between the treadmill and overground match simulations.

Methods

Participants

Twenty healthy male recreational soccer players volunteered to participate in the study. An a priori power calculation was conducted to estimate the sample needed to establish differences between simulations. Based on the data from previous studies (Borotikar, Newcomer, Koppes, & McLean, 2008; Chappell et al., 2005; McLean &

Samorezov, 2009) focusing on the effects of fatigue on lower limb mechanics, it was estimated that a minimum sample size of approximately 15 participants was required to achieve 80% statistical power, and with an alpha level of 0.05. Participants trained 1 to 2 days per week, for 1 to 2 hours per training session. The mean (±SD) age, height, body mass were 26 ± 5 years, 1.74 ± 0.07 m, 73 ± 7.8 kg, respectively. Participants were questioned on their injury history and none had previous ACL injury and all had been free from any other knee or thigh injury within the previous 6 months that could interfere with their performance of utility skills. Written consent was obtained from all the participants and the study was performed in accordance with the university ethics committee guidelines.

Experimental design

In a single group repeated measures design, participants were required to attend the laboratory for 3 separate sessions (one familiarisation and two testing). Participants attended the laboratory having been requested to perform no vigorous exercise or consume any alcohol or caffeine in the 24 hours prior to testing. During the familiarisation session, participants were familiarised with the cutting manoeuvre and the treadmill and overground match simulations for 10 min each. During the first testing session, and after completing a 15 min dynamic warm-up, participants were randomly assigned to perform either the treadmill or overground 45 min match simulation first. Before exercise (time 0 min), immediately at 'half-time' (time 45 min) and after 15 min 'half-time' rest (time 60 min) participants performed five 45° side cutting manoeuvres regardless of the completed match simulation. During the 15 min 'half-time' period participants remained seated and were allowed to drink water. Heart rate (Polar heart rate system, Electro, Finland) and rating of perceived exertion (RPE, 20-point Borg scale) were monitored continuously every five min. The second testing session was undertaken

4 to 8 days after the first testing session, was conducted at the same time of the day, and participants completed the other 45 min match-play simulation.

Soccer-match simulations

The overground match simulation was similar to that devised by Small et al. (2010). The simulation was validated by Lovell, Knapper, and Small (2008) to replicate the fatigue response of soccer match-play. The overground simulation was designed to include multidirectional utility movements, and frequent accelerations and decelerations. To ensure the overground simulation was feasible in our laboratory, and sufficiently frequent acceleration-deceleration movements were performed by the participants, the course distance was modified from 20 m to 15 m. However, participants were required to perform additional course lengths to ensure they completed a similar total distance of approximately 5.39 km (Small et al., 2010). We used a 45 min duration simulation instead of a 90 min duration because lower limb strength (Greig, 2008; Robineau, Jouaux, Lacroix, & Babault, 2012; Small et al., 2010) and knee mechanical (Greig, 2009) changes were primarily observed at half-time with only small further reductions over the second 45 min. Furthermore, high injury incidence in the last 15 min of the first half suggests that 45 min duration may already induce increased injury risk (Hawkins et al., 2001).

The overground simulation required shuttle running over a 15 m distance, with four vertical poles incorporated for the participants to navigate through or around using utility movements (figure 1). The movement intensity and activities (walking, jogging, striding and sprinting) performed by the participants whilst completing the overground course was maintained using verbal cues on an audio recording. A 15 min intermittent activity profile was developed and repeated three times during the 45 min simulated soccer match-play. No contact actions such as kicking or tackling were performed. The treadmill simulation was designed to elicit a similar average running velocity and activity profile as the overground simulation, yet it was conducted on a motorised treadmill (LOKO S55, Woodway GmbH, Steinackerstraße, Germany) imposing slow changes in velocity, thus lower acceleration and deceleration ($0.50\ m \cdot s^{-2}$) than typically observed during the overground protocol. The 15 min activity profile for the treadmill simulation resulted in a distance covered of 1.98 km, giving a 45 min total distance covered of 5.96 km. Whilst having the same velocity profile, lower accelerations and decelerations during the treadmill simulation resulted in a slightly higher total distance than the 5.39 km in the overground simulation. Table 1 shows the average duration spent on one single bout per activity during match simulation.

Assessment of side cutting kinematics and kinetics

To generate the biomechanical markers of ACL injury risk, three-dimensional marker trajectories were collected by 10 infrared cameras at 250 Hz (Oqus cameras, Qualisys, Gothenburg, Sweden) and forces collected by a 0.9 x 0.6 m force platform (Kistler, Winterhur, Switzerland) embedded in the floor, sampling at 1500 Hz. The same investigator placed 44 reflective markers on all participants. A full-body six-degrees-of-freedom kinematic model (the LJMU Lower Limb Trunk model) with functional hip and knee joints was applied using Visual3D (C-motion, Germantown, MD, USA) with segmental data based on Dempster's regression equations and using geometrical volumes to represent each segment. Full details of the model are described elsewhere (Malfait et al., 2014; Vanrenterghem, Gormley, Robinson, & Lees, 2010).

Marker trajectories and force data were low-pass filtered at 20 Hz (Kristianslund, Krosshaug, & Van Den Bogert, 2012) prior to inverse dynamics calculations. Specifically, the frontal plane knee moment was used to retrieve the peak external knee abduction moments during the weight acceptance phase as defined in Dempsey et al.

(2007). For a side cutting manoeuvre, we describe an abduction moment as that exerted by the environment on the knee joint, which is opposed by an equal and opposite adduction moment generated by muscles and ligaments around the knee. It has been shown that maximum magnitude valgus and internal rotation moments were found within the weight acceptance phase (Besier et al., 2001). Sagittal plane knee joint angles at initial contact were also calculated. The initial contact was defined as the time instant when the foot made contact to the ground.

To ensure an approach speed of 4.0 - 5.0 $m \cdot s^{-1}$ prior to the side cutting manoeuvres (Vanrenterghem, Venables, Pataky, & Robinson, 2012), approach speed was recorded using photocell timing gates (Brower Timing System, Utah, USA) that were placed 2 m apart and 2 m from where the side cut was executed. The side cut involved a sudden anticipated change of direction using the dominant right limb (all participants were right limb dominant) to the left at 45° to the initial approach, whilst landing with the right foot on the force platform. The participants' dominant limb was determined as the limb used to kick a ball. Males have been found to be more likely to injure the ACL in their kicking limb (Brophy, Silvers, Gonzales, & Mandelbaum, 2010). The 45° cutting angle was marked on the platform with tape to provide a visual indication of the required exit direction from the task. Cones were also placed 3 m from the force plates to mark a target gate at the required 45°. To limit inter-trial variability, a successful trial was only valid if approach speed was within the required range, and the stance foot landed entirely on the force plate.

Statistical analyses

Paired t-tests were used to compare pre-exertion (time 0 min) conditions (overground vs. treadmill). This was conducted to assess baseline assumption (pre-exertion was equal between simulations). Subsequently, a 2 (simulation: treadmill, overground) × 3 (time: 0 min, 45 min, 60 min) repeated measures analysis of variance (ANOVA) was conducted for each dependent variable using the statistical software package SPSS (Version 20; SPSS Inc., USA). Mauchly's test of sphericity was used to check for equality of variance between simulations and different times. If the Greenhouse‑Geisser epsilon was >0.75 the Huynh Feldt correction was used, if the epsilon was <0.75 the Greenhouse Geisser correction value was used (Girden, 1992). Bonferroni procedures were used for post-hoc analysis. Match simulations and time were treated as independent variables. The dependent variables used in this study included peak knee abduction moment at weight acceptance phase and knee extension angles at initial contact. Each of the five trials was averaged. The alpha level was set at 0.05.

Results

One participant was unable to complete the full protocol. All data reported are for the remaining nineteen participants.

The mean heart rates during exercise (time 5 min to 45 min) for the treadmill and overground simulations were 142 ± 5 and 160 ± 7 beats · min^{-1} respectively, with a significant interaction observed between simulation and time ($F_{3.2,57.8} = 10.2$, $P < 0.001$; Figure 2a). While heart rates increased over time within each simulation ($P < 0.001$), the heart rates increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$). Similarly, the mean RPE during exercise (time 5 min to 45 min) was 12 ± 2 and 15 ± 2 for the treadmill and overground simulations respectively, with a significant interaction between simulation and time ($F_{3.5,63.5} = 14.8$, $P < 0.001$; Figure 2b). While RPE increased over time within each simulation ($P < 0.001$), the RPE increased significantly more for the overground simulation relative to the treadmill simulation ($P < 0.001$).

In the peak knee abduction moments, there was no significant interaction between simulation and time ($F_{2,36}$ = 0.49, P = 0.619. Similarly, no significant differences between simulations ($F_{1,18}$ = 3.82, P = 0.066) or over time ($F_{2, 36}$ = 2.96, P = 0.064; Figure 3a, 4a) were observed.

There was no significant interaction between simulation and time ($F_{2,36}$ = 2.61, P = 0.087), or any significant differences observed in knee extension angles at initial contact between simulations ($F_{1,18}$ = 0.78, P = 0.388). However, a significant change was observed over time ($F_{1.2,22.8}$ = 4.94, P = 0.029; Figure 3b,4b). Pairwise comparisons revealed that knee extension angles increased (became more extended) at time 60 min compared to time 0 min (P = 0.027), and time 60 min compared to time 45 min (P = 0.009).

Discussion

The main findings of the present study indicate that two different types of soccer match simulations, matched for average running velocity, elicited significant differences in heart rate and RPE values, with the overground simulation inducing a greater physiological response. Although similar outcomes were observed when comparing peak knee abduction moments, significant increases in knee extension angles were observed in both simulations at time 60 min, after 15 min of rest. More extended knee joint angles at initial contact have been theorised to increase the likelihood of ACL injury, which will be addressed below.

Effects of soccer match simulations on physiological parameters

Our results show that the overground match-play simulation induced a greater physiological response compared to the treadmill simulation. The total distances covered during the overground and treadmill simulation were 5.39 km and 5.96 km respectively. For comparison, it has been reported that the distance covered during the first half of a male soccer match ranges from 4.13 km to 5.76 km (Bangsbo et al., 1991; Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004). With a shorter overall distance and similar velocities, one might expect there to be less impact from the overground match simulation. The mean heart rate response in the overground simulation (160 ± 7 beats · min^{-1}) was consistent with values reported during match-play (Bangsbo, 1994; Krustrup et al., 2006; Mohr et al., 2004; Thatcher & Batterham, 2004; Van Gool, Van Gervan, & Boutmans, 1998) . However, the mean heart rate in the treadmill simulation (142 ± 5 beats · min^{-1}) was substantially lower, even if they were still higher than 125 beats · min^{-1} as reported in a treadmill match simulation study (Greig, McNaughton, & Lovell, 2006) . It is likely that the heart rate values in our study were higher as our participants were recreationally active as opposed to semi-professional players. An increased heart rate response was supported by the increased RPE during both simulations. Our RPE values were consistent with previous studies using overground (Nicholas, Nuttall, & Williams, 2000) and treadmill (Greig et al., 2006) simulations. As overall running velocity was matched between simulations, we attribute the lower heart rate and RPE response shown during the treadmill simulation to the absence of high acceleration-deceleration and multidirectional utility movements. Research has observed approximately 500 acceleration-deceleration movements during a football match (Bloomfield, Polman, & O'Donoghue, 2009), which has been shown to increase eccentric muscle stress (Small et al., 2010) and was suggested as an important factor associated with injury risk (Woods et al., 2004). The close similarities between physiological responses observed during the present study and values reported from actual match-play justify the use of overground simulations for replicating the demands of soccer, more so than treadmill simulations.

Effects of soccer match simulations on peak knee abduction moments

Our results indicated that both the treadmill and overground simulation showed no differences in peak knee abduction moments. This finding is consistent with Sanna and O'Connor (2008) whilst in other studies an increase in peak knee abduction moments has been reported (Borotikar et al., 2008; Chappell et al., 2005; McLean et al., 2007; Tsai et al., 2009). This discrepancy can be explained through differences in task and type of simulation used. Firstly, anticipated side cutting is a relatively simple task and does not require maximum amount of force. Participants may have retained sufficient ability to complete the manoeuvre without excessive loading the knee joint. The demands of unanticipated side cutting have been shown to induce greater differences in electromyographic responses (Besier et al., 2001) and knee mechanics after fatigue (Borotikar et al., 2008) compared to the anticipated side cutting manoeuvre. Secondly, those studies which observed increased peak knee abduction moments utilised jump tasks and/or high intensity, short duration (< 10 min) exercises designed to induce a level of volitional exhaustion. In our study, a 45 min soccer match simulation was believed to be more representative of the demands associated with actual match-play.

Effects of soccer match simulations on knee extension angle at initial contact

Our study observed significant effects on the knee extension angle at initial contact after 15 min of passive rest in both simulations. A similar treadmill-based match-play simulation has also induced a more extended knee at initial contact (Greig, 2009), although care should be taken in this comparison as their task involved a 180° cut rather than a 45° side cutting manoeuvre. Both are functional soccer movements yet they induce different mechanical challenges, with our task being a running change of direction rather than a complete stop-start movement. This difference likely explains that in our study the knee was much more extended (approximately 13° versus 30°), and the effect of the match-play simulation was less (2° versus 9°). The passive half-time interval did not restore knee joint angles to pre-simulation values, and the knee was more extended after half-time than at the start of the half-time interval. A more extended knee can lead to higher strain of the ACL in combined loading situations (Markolf et al., 1995) and expose the knee to excessive anterior shear force mechanisms (Hashemi et al., 2011). With the knee approaching full extension at initial contact, the capability of the knee to effectively absorb shock is decreased (Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003). Furthermore, this also places the hamstrings at a mechanical disadvantage in which they are unable to contract strongly enough to produce a large posterior force (Pandy & Shelburne, 1997). In fact, a certain abduction moment at the knee is expected to cause more strain on the ACL ligament when the knee is in a more extended position (Markolf et al., 1995). Other studies investigating performance following half-time have similarly observed impaired sprint (Mohr et al., 2004) and sprint kinematic performance (Small et al., 2009), which the authors attributed to lowered body temperature. These findings indicate that consideration should be given to active re-warm up strategies during the half-time interval which, as recently shown, would complement the physiological benefits associated with activity before the second half (Lovell, Midgley, Barrett, Carter, & Small, 2013).

Limitations

The present study has revealed that overground simulated match-play is more representative of actual match play than treadmill based simulations. Nevertheless, neither of those simulations included actual ball handling skills or the presence of an opponent, and all observed movements were fully anticipated. Future research might consider the inclusion of unanticipated tasks in the match simulation, as well as the evaluation of biomechanical markers of injury risk during unanticipated tasks. Also, the biomechanical observations made were only and limited to the observation of previously identified markers of injury risk. It may well be possible that further interrogation of the movement kinematics and kinetics would still reveal effects of match simulation, for example through the use of more comprehensive statistical approaches such as Principal Component Analysis or Functional Data Analysis (for a general overview of these methods, see for example Deluzio, Harrison, Coffey, and Caldwell, 2004). Whilst such analyses could highlight other potentially relevant movement adaptations, the relationship of any such adaptations with injury risk would still remain largely unknown.

Conclusions

To our knowledge, this was the first study to report changes in heart rate, RPE, and knee joint mechanics directly comparing running velocity matched treadmill and overground soccer match simulations. The overground simulation imposed significantly higher heart rate and RPE response than treadmill simulation, likely due to the inclusion of utility movements and higher accelerations and decelerations. For this reason, the overground simulation is believed to better represent actual match-play demands, and is expected to be more suitable for use in further investigation into the effect of match-play on ACL injury risk. We nevertheless found no different effects between treadmill and overground simulation on biomechanical risk factors of ACL injury in male recreational soccer players. Neither simulation elicited changes in peak knee abduction moments or extension angles. However, knee angles at initial contact tended to be more extended following 15 min half-time interval, which may have implications for ACL injury risk.

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Tables

Table 1. Average duration spent on one single bout per activity during match simulation.

Activity	**Time (s)**
Standing (0.0 km · h^{-1})	4
Walking (5.0 km · h^{-1})	17
Jogging (10.3 km · h^{-1})	10.4
Striding (15.0 km · h^{-1})	7.5
Sprinting ($\geq$ 20.4 km · h^{-1})	2.45

Figures

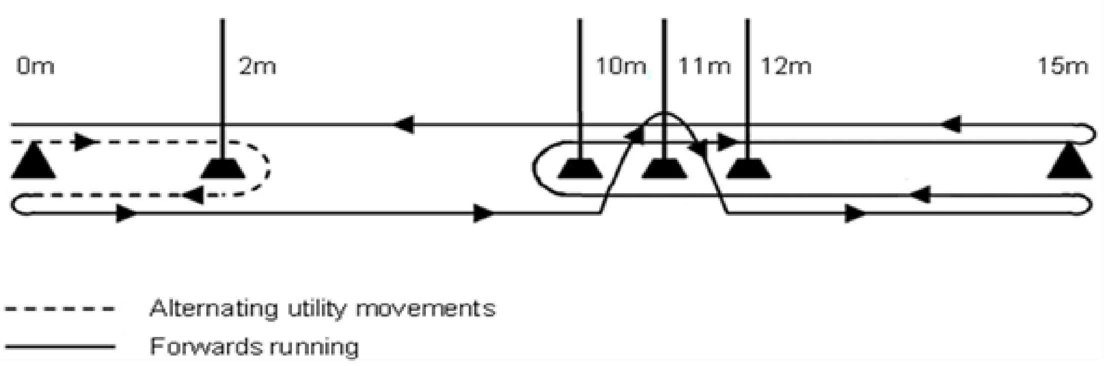

Figure 1. A schematic diagram of the overground match simulation. The simulation was performed with the participants performing either backwards running or side stepping around the first field pole (dashed line), followed by forwards running through the course, navigating the middle three field poles.

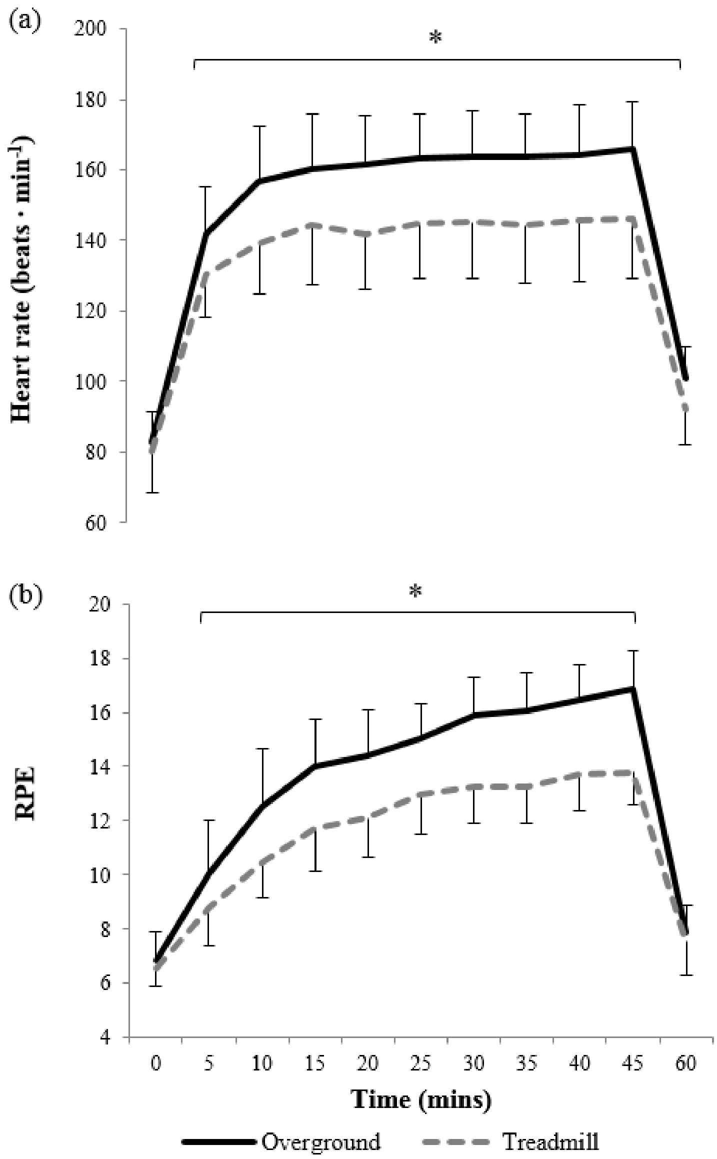

Figure 2. Heart rate (a) and RPE (b) changes over time during treadmill and overground simulations. * Indicates a significant difference between simulations.

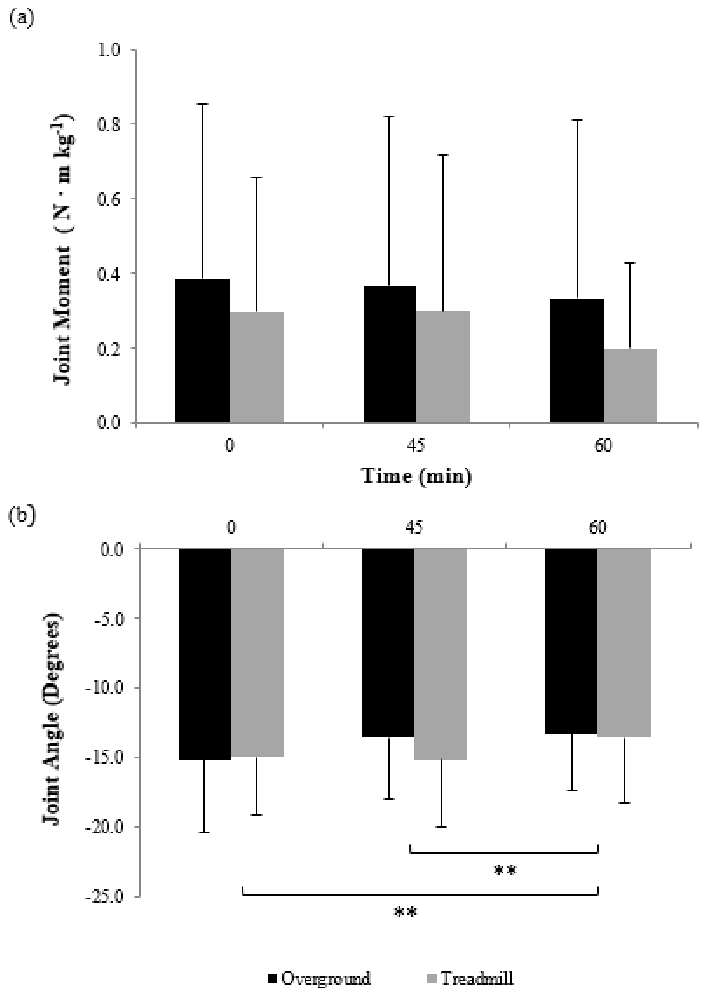

Figure 3. Peak knee abduction moments (a) and knee extension angles (b) during treadmill and overground simulation. **Indicates significant difference over time.

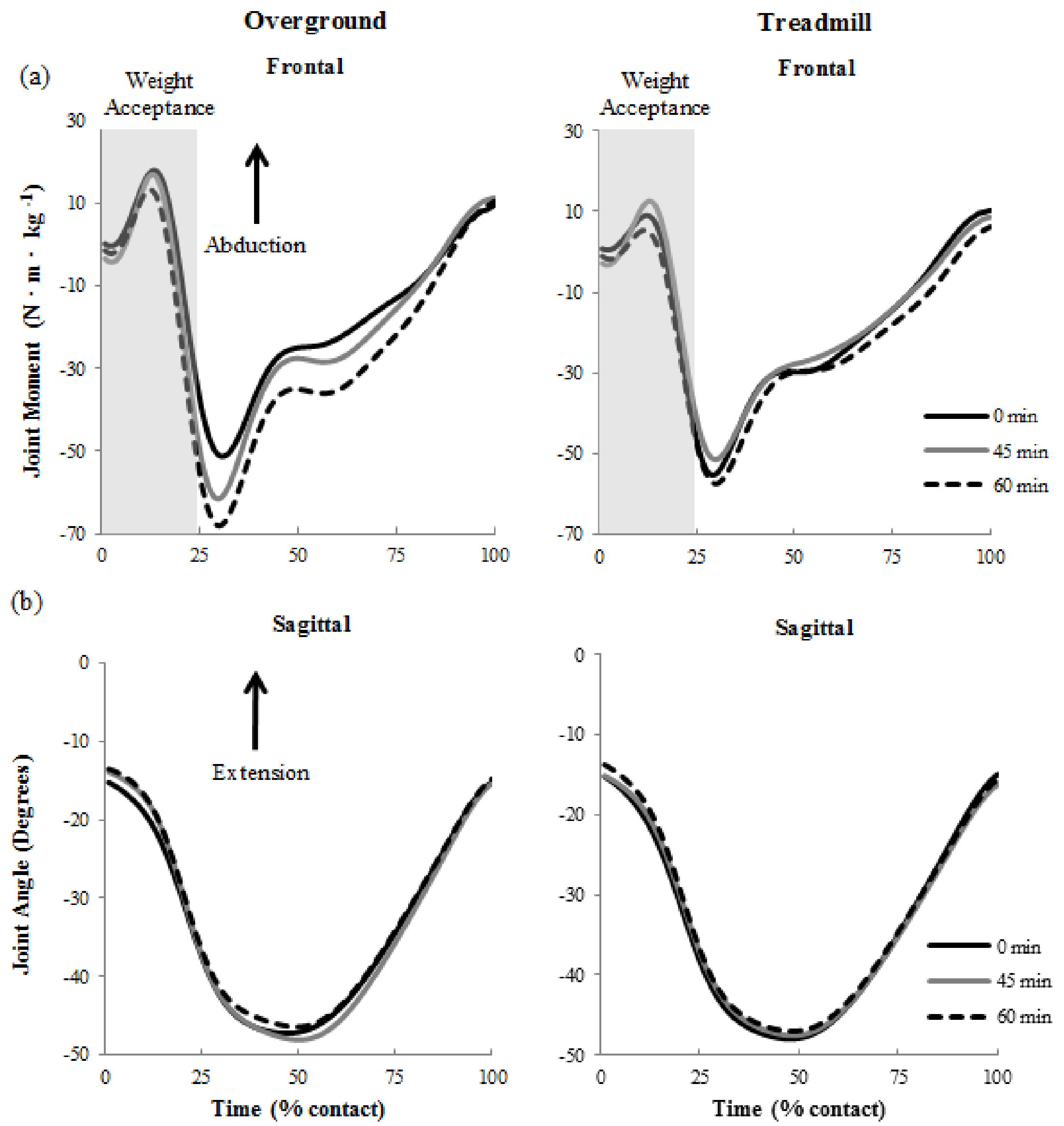

Figure 4. Peak knee abduction moments at weight acceptance phase (a) and knee extension angles at initial contact (b) during treadmill and overground simulation.