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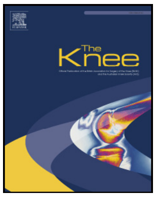

The combined impact of a perceptual–cognitive task and neuromuscular fatigue on knee biomechanics during landing

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ABSTRACT

Background: A large majority of anterior cruciate ligament (ACL) injuries are non-contact, most often occurring during a landing or change of direction. Recent research indicates that cognitive factors may be involved in non-contact ACL injuries. The aim of this study was to determine if a game-situation perceptual–cognitive load leads to altered landing kinematics in physically fatigued female athletes.
Methods: Nineteen female recreational athletes were recruited to perform a series of jumping and landing trials. In a first phase, eight trials were performed in an isolated condition and eight were performed while participants performed a perceptual–cognitive task. Before a second identical phase, participants underwent a muscular fatigue protocol. Knee-joint kinematics were recorded and compared between conditions using paired t-tests.
Results: Muscle fatigue led to statistically significant increases in peak knee abduction and peak internal knee rotation as well as a decrease in maximum knee flexion, when comparing conditions without the perceptual–cognitive task. The perceptual–cognitive task had no statistically significant effect on any knee rotations, either pre- or post-fatigue. However, a subgroup of 12 athletes showed a significant increase in knee abduction in the presence of the perceptual–cognitive task, only in the fatigued condition.
Conclusion: A perceptual–cognitive task combined with muscle fatigue alters knee kinematics of landing for a subset of recreational athletes, potentially increasing the risk of ACL rupture. Further studies are necessary to confirm this finding and to identify characteristics of at-risk individuals to target them for injury prevention protocols.

1. Introduction

The anterior cruciate ligament (ACL) is an important ligament in maintaining knee joint stability. Ruptures of the ACL are amongst the most frequent sports-related injuries, with an incidence of up to 200,000 per year in the United States alone [1]. A large majority of such ruptures, reported to be between 72 and 95%, are non-contact injuries [2,3]. Non-contact ACL-injuries most frequently occur during landing or changes of direction (cutting) [4–7]. The injury mechanism has frequently been associated with a valgus knee and shallow knee flexion [4,8].

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Many traditional injury-prevention protocols for ACL ruptures have focused on muscle strengthening and neuromuscular control [9]. Indeed, several studies have shown that muscle fatigue induces changes in the lower-limb kinematics of landing that may increase the strain on the ACL [10–13]. Fatigue is said to increase the risk of injury due to inadequate active joint stabilization caused by a suboptimal muscle activation strategy [11,14,15]. This is consistent with observations that a majority of ACL injuries occur at the end of a half or end of a game, when fatigue is highest [16,17]. Muscle strengthening delays the onset of muscle fatigue and therefore, it is assumed that it plays a role in reducing or delaying fatigue's negative effects on landing biomechanics. Strength training alone has not reduced the prevalence of non-contact ACL injuries and this may be in part due to an incomplete understanding of neuromuscular risk factors [9,11,14,18].

Several studies have recently investigated the effect of instructing athletes on which limb to land only once they had initiated their jump, preventing pre-planning of their movement [19]. This decision making led to altered landing biomechanics, where knee abduction and abduction moments were increased [20–23]. These alterations were shown to be larger in the presence of muscle fatigue [11,12]. Other studies have also shown a link between cognitive factors and non-contact ACL injuries. In one such study, team-sport athletes that suffered non-contact ACL-injuries were shown to have significantly slower reaction times and processing speeds, as well as lower visual and verbal memory scores during their preseason tests, when compared to matched control athletes [24]. These results indicate that athletes with poorer neurological performance may be at increased risk of ACL injury. Such individuals may include recently concussed athletes, who conserve deficits in mental performance even in the absence of symptoms [25,26] and who were recently shown to have a 2.5 times higher incidence of non-contact lower-limb injury (a majority of which being ligament sprains/ruptures) than a group of matched controls [27]. In another example, a study of 1718 athletes over a 20-year period showed that most ACL injuries were non-contact and a larger percentage occurred in competition (49.2%) in comparison to practice (34.8%), despite much more time being spent in practice [28]. It is proposed that this is due to the higher mental stress incurred during game-situation competition.

Indeed, athletes participating in team sports need to extract and process large quantities of information from their visual field. This perceptual–cognitive ability is an important aspect in explaining on-the-field performance [25]. Studies in a laboratory setting do not typically solicit this ability and it is difficult to study biomechanics in real team-sport game-situations. Recent studies in the field of sports performance have used a three-dimensional (3D) multiple-object tracking (MOT) [26] task to simulate the perceptual–cognitive task required of team-sports athletes in game-situation [27,28]. This task has been shown to be related to the competitive level of athletes [27] and to have a strong correlation with objective measures of performance in team sports [29]. The MOT task therefore has the potential to be used in a laboratory setting to evaluate the effects of a game-situation cognitive load on biomechanics. To our knowledge, no previous study has used MOT or any other similar perceptual–cognitive task for such a purpose.

The purpose of the present study was to measure the effect of this perceptual–cognitive task, used to simulate a game-situation cognitive load, on knee-joint kinematics during landing and cutting movements. This effect was evaluated before and after a protocol to induce muscular fatigue in the lower limbs. Our hypotheses were that: (1) A perceptual–cognitive task during a jump and landing leads to significant changes in knee kinematics and (2) the changes are greater when the perceptual–cognitive task is combined with muscle fatigue.

2. Material and methods

2.1. Subjects

Nineteen female recreational athletes participated in this study. A power analysis of preliminary results determined that 18 participants would allow to detect differences between the conditions with an α level of 0.05 and 90% power. Participation was limited to single-sex athletes to reduce variability of landing kinematics given that gender-related differences have been reported [14,30]. Female athletes were chosen because they are more prone to ACL injury [31]. At the time of evaluation, all of the participants had practiced their sport at least twice a week for at least one year. This inclusion criterion was to ensure a minimal level of athletic conditioning required to complete the physically demanding protocol. The practiced sports were Crossfit ($n = 10$), running ($n = 6$), basketball ($n = 2$) and soccer ($n = 1$). Exclusion criteria were: having had a lower limb injury in the previous six months; having undergone a lower limb surgery; feeling any lower limb pain at the time of testing; having previously undergone perceptual cognitive training; and being under medication that may affect attention and vigilance. Moreover, all participants were asked to refrain from physical exercise for at least 24 h before testing. Approval for the project was gained through the Ethics Committees of CHUM Research Center and Ecole de technologie superieure (ETS). Informed written consent was obtained from each participant prior to their participation.

2.2. Experimental protocol

Participants performed a series of jumping tasks that were composed of a double-foot forward leap, single-leg landing and a lateral cutting movement upon landing, with and without a simultaneous perceptual–cognitive task. The leg on which to land and the presence or not of the perceptual–cognitive task were determined pseudo-randomly for each trial before the beginning of the experimentation. Each participant thus landed on each foot six times with the cognitive task and six times without, for a total of 24 jumps. Following these jumps, the participants went through a muscle fatigue protocol to fatigue the muscles of the lower

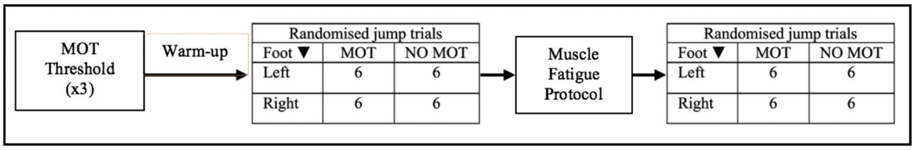

Figure 1. The different steps of the experimental protocol.

limbs (mainly the hamstrings, quadriceps and gluteus maximus) and then repeated the series of 24 jumps, under the same experimental protocol (Figure 1).

Participants were asked to wear spandex shorts and a sports bra. A 12-camera optical motion capture system (Vicon T20, Oxford, UK) was used to record bilateral lower limb kinematics for each trial. Individual reflective markers and marker clusters were placed on the participants. These consisted of a belt placed tightly over the pelvis (just below the anterior superior and posterior superior iliac spines), two femoral clusters, two tibial clusters, six individual markers on each foot, and a total of four markers placed over each of the lateral and medial epicondyles (Figure 2). A functional calibration consisting of a series of participant-performed movements was used to define joint centers and anatomical axes, as described by Hagemeister et al. [32].

2.2.1. Jumping task

Each trial consisted of a forward jump from a static position on both feet, a landing on a single leg within the limits of a force plate and an immediate lateral cutting movement onto a second force plate, which was situated 30 cm to either side of the first force plate. Ground reaction forces from the force plates were used for delimiting the landing movements within the kinematic recordings, actual forces are not reported here. To establish the starting position, each participant was asked to perform three jumps at their maximum distance while landing on one foot. The mean of the three jump distances was used as the distance for the subsequent jumps. This was done to normalize the task relative to each participant's ability. Preliminary trials found that using a fixed distance that all participants could reach resulted in the task being overly easy for some of them. For these participants, the biomechanics of the individual jumps varied greatly. Before the start of each jump, the experimenter told the participant on which leg to land. If she was to land on her right foot, she had to land on the right force plate and cut onto the left one, and vice-versa.

2.2.2. Perceptual–cognitive task

MOT consists of visually tracking a subset of eight identical spheres that move in three-dimension. Each task consists of five successive steps (Figure 3): eight identical spheres are shown in a virtual volumetric space (a); the target spheres (in this study there were three targets) are indexed by changing color for a one-second period (b); all spheres return to their original color and start moving in randomized directions with dynamic interactions (bouncing off of each other and off the virtual 3D volume boundaries and occluding each other) for eight seconds (c); the movement stops and the participant is asked to identify the target spheres (d); the actual targets are revealed and juxtaposed with those identified by the participant.

In order for participants to have a similar degree of cognitive loading, the target-movement speed was normalized according to their individual speed threshold, which is known to vary greatly between individuals [30]. To establish the threshold, the 3D-MOT task is performed once at an arbitrary speed. If all three targets are not correctly identified, the next trial is slower. If the three spheres are correctly identified, the next trial is faster. This is repeated following a staircase procedure until a speed threshold is established [33], defined as the mean of the last six speeds. For this study, each participant's threshold was measured three times, consecutively, and the results were averaged. During the jump task, the speed of the spheres was set to 30% of the participant's mean threshold. In preliminary trials, this value was found to be the highest at which participants were able to consistently succeed in tracking three targets while doing the jump task.

The 3D-MOT was presented using “Neurotracker” software (CogniSens Athletics Inc., Montreal, Canada) projected onto a 280-cm screen with a 3D projector. The participants were at a distance of 130 cm from the screen (for threshold and at starting position of jump task) and were wearing stereoscopic glasses. For 3D-MOT trials performed during jumping trials, the participant was instructed to initiate her jump immediately after the spheres had begun moving, giving sufficient time for the entire task to be executed during their movement. Any jump where the participant did not correctly identify at least two of the three indexed targets was considered unsuccessful and was started over. This was done to avoid instances where the participant lost track of the targets and focused all of her attention to the jumping task, essentially ignoring the perceptual–cognitive task.

2.2.3. Muscle fatigue protocol

In order to induce muscle fatigue, participants executed series of 15 one-legged squats, alternating legs between each series. This was repeated until the participant could no longer complete the full series on either leg. To minimize recuperation during the execution of the landing tasks, participants performed an additional six one-legged squats on each leg after every second jump. The objective was to avoid recovery and maintain high muscle fatigue throughout the fatigued trials. Previous studies have shown that the changes in landing biomechanics are similar from 50% fatigue through to maximum fatigue [11,12].

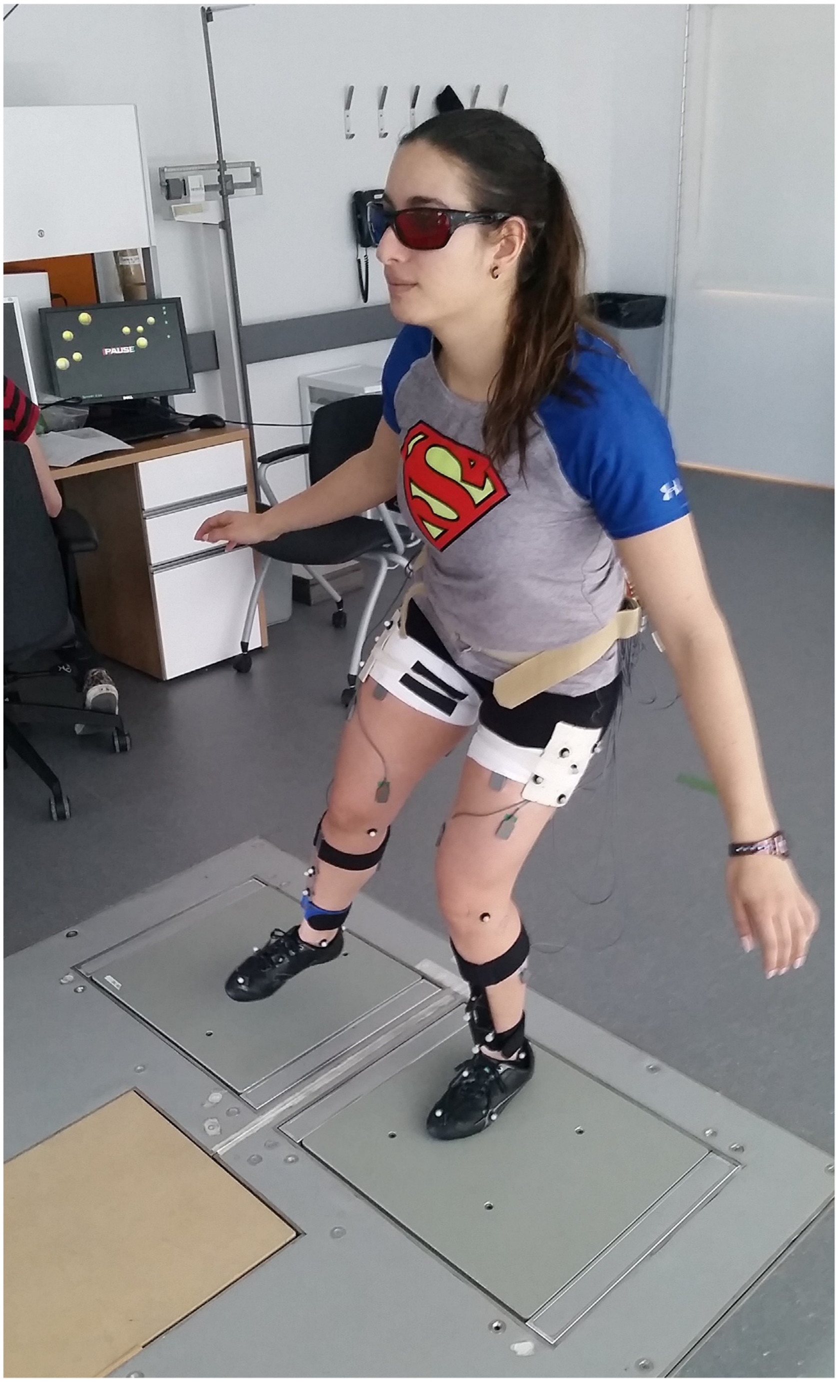

Figure 2. A participant performing the task while wearing the motion capture markers.

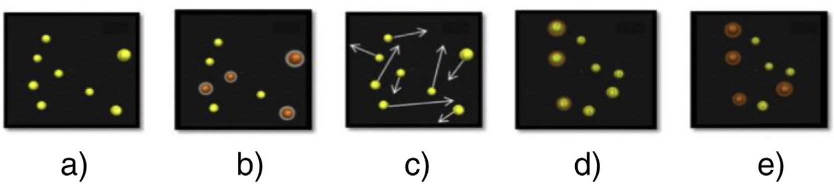

Figure 3. The five steps of the 3D multiple object tracking (3D-MOT) task.

2.3. Data analysis

Anatomical calibration to define the bone-embedded axes was performed using the FP method[2] and axes are defined as described by Grood and Suntay [34]. Knee-joint rotations in all three planes were extracted from the raw kinematic data. The kinematics of a landing were defined as starting when the vertical ground reaction force attained two percent of its maximum value. Similarly, the end of the landing was set when the vertical ground reaction force went back under two percent of its maximum value. Therefore, the kinematic data for each trial includes the landing and push off of the lateral cutting movement. Points of interest for further analysis were the rotational values at initial contact (using the two percent cut-off) and at the peak value for each knee rotation.

For each condition (pre-fatigue, pre-fatigue with 3D-MOT, post-fatigue and post-fatigue with 3D-MOT), the mean and standard deviation were computed for all three knee rotations at both of the aforementioned points of interest. The Shapiro–Wilk test (alpha = 0.05) was used to verify normality of these data and paired t-tests were used to compare the results between conditions. The level of statistical significance was set at $p < 0.05$. K-means clustering was applied to the kinematic data to identify subgroups that may have been affected differently by fatigue and the 3D-MOT task. The elbow test was used to determine the number of clusters.

3. Results

All 19 participants completed the entire study. They were 25.0 years of age (s = 2.4 years), weighed 82.2 kg (s = 13.5 kg) and were 177.1 cm (s = 5.8 cm) tall. Sixteen participants self-reported right-limb dominance and three, left-limb dominance (defined as the foot with which they could kick a soccer ball the furthest). Normalization of jumping distance resulted in the starting line for the jumping task being set at an average of 141.1 ± 15.5 cm from the force plates. Participants were able to complete an average of 119 ± 42 squats on the right leg and 118 ± 42 on the left leg before attaining maximal muscle fatigue. The speed threshold at which they were able to successfully track the indexed targets was 1.24 ± 0.30 m/s and they failed to correctly identify at least two of the targets (and thus had to redo the jump) 2.6 ± 1.0 times, out of a total of 16 jumps with MOT. For one participant

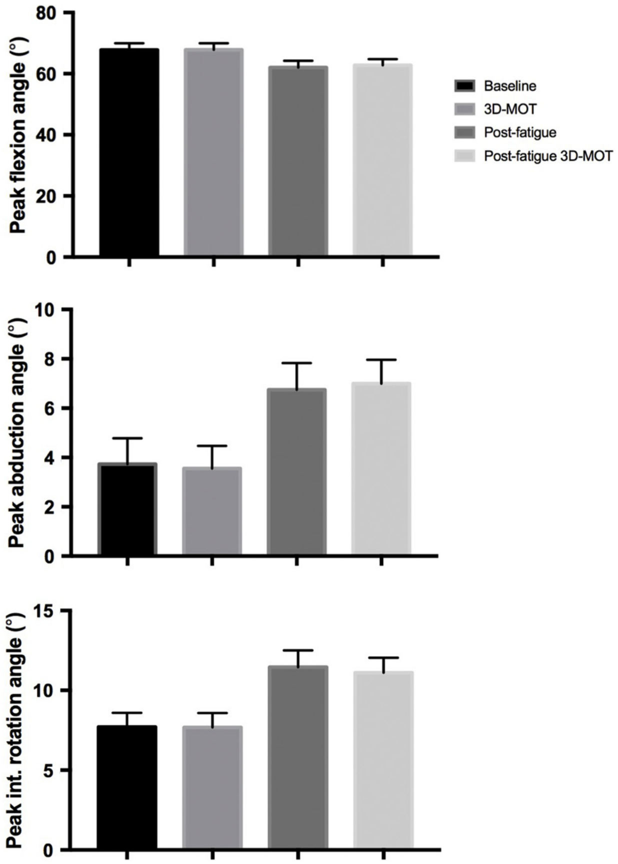

Figure 4. The peak flexion, abduction and axial rotation angles across all subjects, for all experimental conditions.

Table 1
Mean and standard deviation values at initial contact (IC) and peak values (PV), with and without a simultaneous 3D-MOT task, before and after a muscle-fatigue protocol.

Knee rotations (°)	Pre-fatigue		Post-fatigue	
	Isolated	3D-MOT	Isolated	3D-MOT
Flexion (IC)	25.8 (±9.9)	26.6 (±10.4)	23.2 (±8.8)	24.4 (±10.2)
Abduction (IC)	−3.9 (±3.7)	−4.3 (±4.0)	−1.9 (±4.7)	−2.0 (±4.6)
Internal (IC)	−10.5 (±6.8)	−11.1 (±7.3)	−8.5 (±7.8)	−8.5 (±7.1)
Flexion (PV)	67.8 (±9.5)	67.8 (±9.4)	62.1 (±9.6)	62.8 (±8.7)
Abduction (PV)	3.7 (±4.6)	3.6 (±4.0)	6.7 (±4.7)	7.0 (±4.2)
Internal (PV)	7.7 (±3.8)	7.7 (±3.8)	11.5 (±4.5)	11.1 (±4.0)

(number 1), a missing motion-capture marker prevented the measurement of internal knee rotation so for this parameter, only 18 participants are reported. All other values are reported for 19 participants.

Peak values for knee rotation angles (PV) and angles at initial contact (IC) were normally distributed in all three planes, according to the Shapiro–Wilk normality test. Muscle fatigue led to statistically significant increases in peak knee abduction ($p < 0.0001$) and peak internal knee rotation ($p = 0.0003$) as well as a decrease in maximum knee flexion ($p < 0.0001$), when comparing conditions without the perceptual–cognitive task. Fatigue also impacted knee rotations at initial contact in a similar manner: increase in abduction ($p < 0.001$) and internal rotation ($p < 0.01$) and decrease in flexion ($p < 0.01$). The perceptual–cognitive task had no statistically significant effect on any knee rotations, either pre- or post-fatigue (Figure 4). Table 1 presents the mean knee rotations with standard deviations for all four conditions.

The k-means clustering method revealed two distinct clusters of participants ($n = 7$ and $n = 12$), based on the peak knee joint angles in the post-fatigue with 3D-MOT condition. In the second cluster ($n = 12$), the perceptual–cognitive task led to a significant increase in maximum knee abduction ($p < 0.001$) in the post-fatigue conditions (Figure 5). Prior to fatigue, the 3D-MOT task had no significant effect on any of the knee rotations. Performance in the 3D-MOT task did not differ significantly (1.24 m/s and 1.23 m/s) and none of the kinematic parameters differed between the identified clusters.

4. Discussion

The results obtained in our study show that lower-limb muscle fatigue significantly alters the knee kinematics of landing and that for a subset of participants, a perceptual–cognitive task combined to the muscle fatigue further increases knee abduction. The results therefore do not support the hypothesis that a perceptual–cognitive task alone causes significant changes to the knee biomechanics of landing. When considering the entire group of 19 participants, the hypothesis that the combination of muscle fatigue and a perceptual–cognitive task increases kinematic changes is also unsupported but it is supported for a large subset of the sample population, composed of 12 participants.

Indeed, results of the current study show that muscle fatigue leads to significant changes in the knee kinematics of unilateral landing, both in maximum values and values at initial ground contact. The changes that were observed (increased abduction and internal rotation combined with decreased knee flexion) are in agreement with results of several previous studies [10–12,15], although other studies have reported increased knee flexion with fatigue [14,35]. These three changes have been linked to a higher

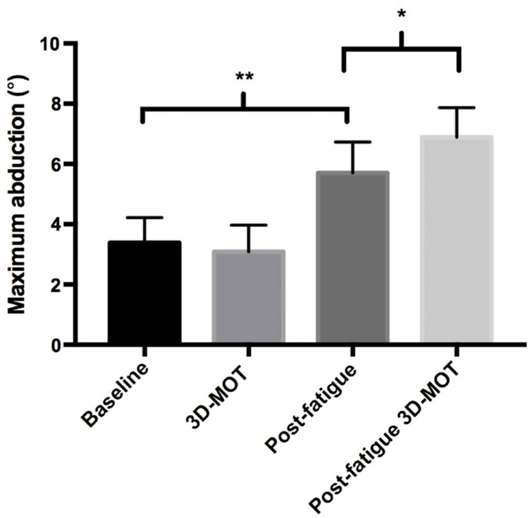

Figure 5. The peak abduction angle for the main subgroup, for all experimental conditions. *$p < 0.001$, **$p < 0.0001$.

risk of ACL injury. An increase in abduction angle has been shown to increase ACL strain [36–38] and to prospectively predict ACL injury when observed during a land and jump task [39]. The application of internal rotation torque has also been shown to increase strain on the ACL [38], with one study showing that the combination of increased valgus and internal rotation moments causes a greater strain on the ACL [36]. Landing with less knee flexion increases anterior shear forces on the proximal tibial, also leading to an increase in ACL strain [40,41]. McLean et al. [12] measured the impact of fatigue and of decision making (for landing limb) using a very similar jumping and cutting task and found that fatigue decreased knee flexion by an average of 9.6° and increased knee abduction and internal rotation by 0.6° and 0.4°, respectively. In our study, knee flexion was not decreased as much (5.7°) but abduction and internal rotations increased to a larger extent (3.0° and 3.8°). Differences between these two studies may be explained by the different cognitive tasks that were used as well the difference in populations, as McLean's participants were elite-level athletes.

To our knowledge, this is the first study to examine the effect of a perceptual–cognitive task on landing kinematics. For a subgroup of 12 out of 19 participants, the 3D-MOT task was found to significantly increase peak knee abduction; knee flexion and internal rotation were not significantly affected. Increased abduction, or valgus knee, is the kinematic parameter most frequently associated with ACL injury. A prospective study found that female athletes who subsequently ruptured their ACL performed jump landing tasks with significantly higher valgus moments than athletes who did not rupture their ACL [39]. Fukuda et al. [42] showed that ACL strain increased when valgus moment increased and Shin et al. [37] showed that knee valgus moment increases peak ACL strain during single-leg landing. It is thus posited that this subgroup is at higher risk of an ACL injury in a game-situation where the perceptual–cognitive demands are high and they are physically fatigued. In this condition, the high cognitive demands may prevent these individuals from utilizing their neuromuscular system appropriately to prevent ACL injuries. This is in agreement with the findings of McLean et al. who found that the difference between pre-planned and unanticipated trials became more prominent after the participants were fatigued [12].

Further research is needed to confirm if the identified subgroup in our study is indeed at increased risk of non-contact ACL injury in a game situation and what other characteristics they share. These shared characteristics could be used to identify at-risk athletes without having all of them go through a time-demanding protocol such as the one used in this study. Indeed, much emphasis has been put on identifying individuals who may be predisposed for ACL injuries in order to better target injury prevention protocols [18,19,43]. Today, even the most effective of current neuromuscular training programs would require 70 athletes to participate in order to prevent a single non-contact ACL injury [19]. In this study, the speed at which participants were able to follow target in the 3D-MOT task was not significantly different between the identified clusters. No other characteristics of the participants were found to differ between clusters. This may be partly due to the small number of participants in each cluster (one was comprised of only seven participants). A higher number of participants may allow identifying differences in 3D-MOT performance between those whose landing kinematics are affected by the task and those that are not. Moreover, performance at the 3D-MOT task was only measured in an isolated condition. It is possible that those most affected by the perceptual–cognitive task in the fatigued condition would score lower when performing the task with a simultaneous motor task, where cognitive resources are divided. Swanik et al. [24] has shown that NCAA athletes who incurred non-contact ACL injuries had lower pre-season scores in all categories of the ImPACT test. It would therefore be of interest to investigate if there is a correlation between 3D-MOT and ImPACT scores and if ImPACT score results are different for those who are affected by the 3D-MOT task once fatigued. This would add weight to the theory that these tests are able to identify subgroups of the population that are at higher risk of ACL injury.

The ability required to perform a 3D-MOT task intersects those in the ImPACT test, notably the visual memory and visual attention aspects. Decreased visual memory may be associated with mistakes in coordination [44,45]. It has been proposed that athletes with decreased visual attention skills may have difficulty interpreting and negotiating conflicting information when challenged with unanticipated events [24], leading to diminished visual–spatial orientation and disrupting the execution of routine motor routines. Performance at a 3D-MOT task is highly trainable for all individuals, whatever their initial performance level is [27,46,47]. Training at a 3D-MOT task has been shown to result in improved decision-making in a simulated game-situation for competitive athletes, showing a transfer of improved perceptual–cognitive ability at this non-specific task towards a sport-specific context [28]. It is therefore foreseeable that perceptual–cognitive training such as 3D-MOT training could reduce or eliminate the added kinematic changes that occur when such a task is added in a fatigued condition, thereby reducing the risk of non-contact ACL injury in real game situations.

This study has a number of limitations. First, participants were recreational athletes that practiced different sports including endurance, non-team sports. This assured that all participants were in good physical condition to perform the required tasks. The variability of practiced sports and of skill level was partly mitigated by the fact that length of the jumping task, the speed of the MOT task and the number of squats performed were all normalized to each participant's maximum capacity. However, recreational athletes may react differently to muscular fatigue and/or perceptual–cognitive loading. It has already been shown that elite athletes perform at much higher levels than non-elites at 3D-MOT [47]. Therefore, these findings cannot be assumed to apply to elite athletes. Second, the level of fatigue was not quantified in this study so there may be some intra-participant variability in the actual level of fatigue that was reached and maintained through the fatigue protocol. Previous studies, with similar protocols, have found that the changes in landing biomechanics are maintained from 50% through maximum fatigue [11,12]. Thus, the precise level of fatigue is not critical and the effect of some variability in fatigue level is believed to be limited. Third, previous studies have found that neuromuscular fatigue combined with unanticipated jumps, i.e. when the participant is only informed on which leg to land one the jump is initiated, are a worst case scenario for biomechanical changes that strain the ACL [11] because the unanticipated condition prevents the participant from pre-planning his movement. Such trials were not included in this study because preliminary trials with recreational athletes showed that most were unable to perform unanticipated jumps while also performing a 3D-MOT task so all jumps in this study were anticipated. This may have diminished the effects of the 3D-MOT task on landing kinematics as participants could pre-plan their movements and had less division of their attention during the execution of the jump and landing. Elite-level athletes may have been able to complete a study with unanticipated jumps due to their better perceptual–cognitive abilities or even because of a longer hang time. Finally, because of the nature of the study, the order of the fatigued and non-fatigued conditions could not be randomized. The impact of 3D-MOT practice is believed to have been minimal over so few trials and any effect would have presumably diminished the effect of 3D-MOT on knee kinematics, as participants improved at the task.

Future work will focus on identifying the characteristics that differ between athletes for whom the combination of muscle fatigue and a perceptual cognitive task leads to alteration of landing biomechanics. This work will also aim to verify if these altered knee kinematics are diminished following a perceptual–cognitive training that improves their performance at the 3D-MOT task.

5. Conclusion

A perceptual–cognitive task combined with muscle fatigue alters the knee biomechanics of landing for a subset of recreational athletes, potentially increasing the risk of ACL rupture. Further studies are necessary to confirm this finding and to identify characteristics of at-risk individuals in order to target them for injury prevention protocols.

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