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DOI:
10.1249/mss.0000000000002308

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Smeets, A, Verheul, J, Vanrenterghem, J, Staes, F, Vandenneucker, H, Claes, S & Verschueren, S 2020, 'Single-joint and whole-body movement changes in anterior cruciate ligament athletes returning to sport', *Medicine and Science in Sports and Exercise*, vol. 52, no. 8, pp. 1658-1667.
https://doi.org/10.1249/mss.0000000000002308

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Single-joint and whole-body movement changes in ACL athletes returning to sport

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Abstract

Introduction

Athletes returning to sport after anterior cruciate ligament reconstruction (ACLR) demonstrate prolonged changes in landing kinematics, kinetics and muscle activation, predisposing them for re-injury, knee osteoarthritis and/or knee instability. So far, researchers have been focusing on how kinematics and kinetics change in every joint separately. However, as the human body operates within a kinetic chain, we will assess whether single-joint changes are associated with whole-body changes.

Methods

Twenty-one athletes who had an ACLR and twenty-one uninjured controls performed five unilateral landing tasks while lower limb kinematics, kinetics, and muscle activations of vastus medialis, vastus lateralis, biceps femoris, semitendinosus, semimembranosus, gastrocnemius and gluteus medius were recorded.

Single-joint landing kinematics, kinetics and muscle activations of the ACL-injured leg were compared to the uninjured leg and compared to the control group.

Whole-body changes were assessed by decomposing movements into fundamental components using marker-based principal component analysis (PCA).

Results

We found several single-joint changes in landing kinematics, kinetics and muscle activations in the athletes with ACLR that were seen across all tasks and therefore of major interest as they are likely to occur during sports as well. Hamstrings activation increased and external knee flexion moments decreased in the ACL-injured leg compared to their uninjured leg.

Furthermore, hip adduction moments and knee abduction angles decreased compared to the control group.

The PCA could detect changes in whole-body movement, which were task-specific.

Conclusion

Athletes with ACLR still show protective task-independent single-joint kinematic, kinetic and muscle activation changes during single-leg landings at the time of RTS. These single-joint changes were not consistently accompanied by changes in whole-body movements (revealed by marker-based PCA). Whole-body expressions of the single-joint compensations are likely to be affected by the demands of the task.

Key terms

ACL reconstruction; return-to-sport; biomechanical alterations; PCA

1 Introduction

Anterior cruciate ligament (ACL) injuries commonly occur during dynamic sports activities in young active populations. Although most injured athletes undergo a reconstruction of their ACL, success rates for return to sport (RTS) remain low with post-surgical retirement rates of up to 45% (1) and re-injury rates of up to 15-25% (2). Furthermore, the risk for early development of post-traumatic knee osteoarthritis (PTOA) is increased in athletes that underwent an ACL reconstruction (ACLR), with almost half of these patients having radiographic signs of osteoarthritis 10-20 years after reconstruction (3).

Despite positive developments and extensive research on ACL rehabilitation and RTS criteria over the past decades (4), the prevalence of re-injuries and PTOA is still high. This suggests that athletes return to sport with remaining deficits or compensation strategies because of incomplete rehabilitation. Persistence of strength deficits (5, 6), as well as prolonged neuromuscular and biomechanical deficits (7), are expected to predispose athletes for re-injury, early development of knee osteoarthritis and/or knee instability. Several studies have demonstrated prolonged changes in landing kinematics, kinetics and muscle activation (8–10) after RTS. Two recent systematic reviews (9, 10) concluded that external knee flexion moments were decreased in athletes with ACLR during single- (9, 10) and double-leg landings (9), indicating that altered loading patterns are still present in these athletes at the time of RTS.

Reduced knee flexion moments are kinetic changes that occur at the level of a single joint. Much research has focused on such single-joint alterations (i.e. biomechanical changes in a single joint) by assessing changes in kinematics and kinetics for individual joints separately. However, athletes with ACLR may also show changes in whole-body alterations (i.e. a combination of biomechanical changes in multiple joints) as a result of the simultaneous movement and orientation of multiple segments. Since the human body functions as an integrated series of highly interacting segments within a kinetic chain (11), these single-joint and whole-body movement alterations are likely related with each other. Changes in whole-body movement might be either the result of joint-specific changes, or the underlying mechanical cause for the joint-specific alterations. For example, Oberlander et al. (12) and King et al. (13) found that athletes with ACLR reposition their center of mass to have the ground reaction force (GRF) more anteriorly (i.e. global alteration). This reduces the moment arms to the knee joint which results in reduced knee flexion moments (i.e. local alteration) (12, 13). Whole-body movements are likely to be a closer representation of what practitioners may observe (e.g. during screening or landing technique training) and may thus have clinical relevance. Although changes in whole-body movement can be identified from marker-based principal component analysis (PCA), which allows one to identify fundamental coordination patterns or 'principal movements' (14–16), this technique has not been used to evaluate changes in whole-body movement in athletes with ACLR.

This study aims to combine conventional biomechanical observation (joint kinematics, kinetics and muscle activations) to assess single-joint alterations (i.e. biomechanical changes in a single joint) with marker-based PCA to assess whole-body alterations (i.e. a combination of biomechanical changes in multiple joints) during landing strategies. Through this novel combined approach, we want to emphasize that RTS decision should consider both joint-specific alterations, as well as whole-body compensatory movements. We will focus on alterations that are consistent across different single-leg landing tasks and are thus more likely to appear during sport-specific tasks on the field, increasing their clinical relevance. We hypothesize that athletes with ACLR show both joint-specific and whole-body movement alterations at RTS.

1. Materials and methods

2.1 Participants

Twenty-one patients who have undergone an ACLR (semitendinosus autograft) were included in this study (see table 1). The following inclusion criteria were used: women and men between 16 and 40 years old, all participants had to play a sport that involves cutting, pivoting and/or jumping at an intermediate to high level before their injury (minimum 2 training days/week and 1 match/week) and wished to return to the same sports. All patients completed rehabilitation with their own physiotherapist and were cleared by their surgeon and/or physiotherapist to fully participate in training sessions again. The testing took place maximally 2 weeks before or after the first full training session and the average time post-surgery at the time of testing was 258.6 ± 54 days. Athletes that had a previous serious knee injury or ACL injury before the current ACL injury, were excluded. Furthermore, a control group was included consisting of twenty-one uninjured athletes who were matched for age, sex and type of sport (see table 1). The control subjects were free of lower extremity or back injuries for at least 6 months and had no history of ACL injuries. All participants wore standardized indoor footwear (Indoor Copa, Kelme, Elche, Spain). The participants signed a written informed consent and the study was approved by the local ethics committee with reference number S60182.

2.2 Protocol

All participants performed a standardized warming-up consisting of 5 minutes cycling on a stationary bike, ten squats, and ten squat-jumps at the start of the test session. Subsequently, they performed three static maximal voluntary contractions (MVC's) of 5 seconds for all muscle groups (vastus medialis (VM), vastus lateralis (VL), hamstrings medialis (HM), hamstrings lateralis (HL), gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and gluteus medius (GlutMed). The detailed MVC setup was described in a previous study(17).

After familiarization, participants performed three valid trials of five unilateral tasks (17) on the dominant and non-dominant leg, according to the following instructions:

- *Single leg hop for distance*: to jump as far as possible on 1 leg.
- *Medial & lateral hop:* to jump sideways over a 0.24m high hurdle (1.5cm wide) on 1 leg, to cover a mediolateral distance that was half the leg length (i.e. the distance between the anterior superior iliac spine and medial malleolus).
- *Vertical hop with 90° of medial rotation & vertical hop with 90° of lateral rotation:* to jump as high as possible on 1 leg, while performing an inward/outward rotation of 90°.

The dominant leg was defined as the preferred leg to kick a ball. For all 3 tasks, participants were instructed to take off and land on the same leg. Trials were considered valid if the landing was central on the force plate and the participant could maintain his/her balance for 5 seconds after landing without shuffling on the stance leg.

2.3 Data collection

Three-dimensional kinematic data were collected using 10 MX-T20 optoelectronic cameras (VICON, Oxford, UK) sampling at 100 Hz, synchronized with GRF data recorded from two 46.4x50.8 cm OR6-7 force plates (AMTI, Watertown, USA) sampling at 100 Hz. Each participant had 44 spherical reflective markers positioned according to the eight segment 'Liverpool John Moores University' model including feet, upper and lower legs, pelvis and trunk (18).

A wireless EMG system, type: Cometa Mini Wave (Zerowire, Aurion, Milan, Italy) was used to record muscle activity at 1000 Hz of the VL, VM, HM, HL, GL, GM and GlutMed using surface electrodes positioned according to the SENIAM guidelines (19). Electrode locations were shaved and gently cleaned with 70% isopropyl alcohol to reduce skin impedance. Silver-

silver chloride, pre-gelled bipolar surface EMG electrodes (Ambu Blue Sensor, Ballerup, Denmark) were placed over the muscle belly and aligned with the expected muscle fiber orientations, with 2 cm inter-electrode distance.

2.4 Data analysis

Modelling and data processing were undertaken in Visual 3D (v.6.01.07, C-Motion, Germantown, USA) and MATLAB (R2017a, The MathWorks, Nattick, USA). A 4th order low-pass Butterworth filter with a cut-off frequency of 18 Hz was used to filter marker trajectories and forces. Subsequently hip, knee and ankle kinematics were calculated using a Cardan sequence of rotations and kinetics were calculated using inverse dynamics(20). We reported external joint moments in this study (e.g. an external knee flexion moment will flex the knee).

Raw EMG signals were bandpass filtered (6-240Hz), rectified, and low-pass filtered with a 4th order zero-lag Butterworth filter at a cut-off frequency of 15 Hz. Subsequently, the filtered EMG signals of the jumping tasks were normalized to the peak value obtained during the 3 isometric MVCs.

Initial contact (IC) events were identified using a 10N threshold of the vertical GRF. Only the data of the landing was analyzed, from IC until 500ms after IC. For the EMG data, a short time period (100ms) before IC was included, to account for the maximal expected electromechanical delay. EMG data were thus analyzed from 100ms before IC until 400ms after IC.

2.5 Statistical analysis

To investigate whether athletes with ACLR still show deficits in jumping performance, we compared their jump distance (single leg hop for distance) and jump height (vertical hops with 90° rotation) of the injured leg against (1) the contralateral, uninjured leg and (2) against the control group. A paired t-test was used to assess between limb differences and unpaired t-test to assess differences between the ACL injured legs and the control group. To reduce the possible influence of leg dominance in the comparisons between the ACL injured legs and the control group, we included the same amount of dominant and non-dominant legs in the control group (randomly selected).

To investigate whether ACL reconstructed athletes still show single-joint deficits or compensation strategies at the time of RTS, we compared their landing kinetics, kinematics and muscle activation patterns with (1) the contralateral, uninjured leg and (2) against a control group. To avoid unjustified reduction of data to discrete values such as mean or peak values, we used one-dimensional Statistical Parametric Mapping (SPM1D version M.0.4.5, www.spm1d.org) for our statistical analysis. SPM1D calculates descriptive test statistics at each time node, but avoids the problem of multiple comparisons by modeling the behavior of random time-varying signals for inference calculations(21). The time periods that have a test statistic exceeding the critical threshold are called supra-threshold clusters and indicate the landing phase(s) with significant differences between groups. For every supra-threshold cluster the average p-value is calculated.

Paired SPM1D t-tests were used to assess between-limb differences in landing patterns in the ACL athletes. Unpaired SPM1D t-tests were used to investigate differences in landing patterns between the injured legs of the ACL group and the control group. In the ACL group, eight athletes injured their dominant leg and thirteen athletes their non-dominant leg.

Since this study is an explorative study, no adjustment for multiple testing was performed. This strategy avoids increasing the risk for false negatives (type II errors) which is desirable in explorative studies but one should be aware that this also has the disadvantage of increasing the risk for false positives (type I errors) (22–24). Therefore, we want to stress that the results of this study are all explorative and need to be confirmed by other studies.

To assess changes in whole-body movement, we performed PCA on the marker data. This technique decomposes movements in different principal components (PCs) that each represents dominant movement strategies or principal movements (PMs)(14–16). After normalization and scaling, PCA was performed on the combined marker trajectory data for each task (Supplemental Digital Content 1, detailed description of marker-based PCA method). The PCA has three outcomes: eigenvectors that describe the directions of the variability in the data, eigenvalues that describe the amount of variance explained by the eigenvector, and time evolution coefficients (PC scores) that represent the level of expression of each PM in each participant. In search of changes in landing strategies between (1) the injured and uninjured leg of the ACL group and (2) the ACL injured leg and the control group, we assessed which PMs were expressed more or less in a certain group compared to another group by comparing time evolution coefficients(25). Paired SPM1D t-tests were used to compare the time evolution coefficients between the injured legs and the uninjured legs of the ACL group, and unpaired SPM1D t-tests to assess differences in expression between the ACL injured legs and the control group. Only those PMs that had significant differences in their time evolution coefficients between both groups ($p<0.05$), as well as a Cohen's effect size >0.5 were retained(26).

To visualize differences in PMs, we created overlaying stick figures that represent the groups (control, ACL injured and ACL uninjured group). Marker positions for these stick figures were calculated by transposing the retained PM for each group onto the mean posture vector of the control group(25). This approach allows for the visualization of between-group differences in individual PM patterns. An amplification factor was used to exaggerate differences in the stick figure visualizations to better demonstrate between-group and between-leg differences. Finally, PMs were described based on visual inspection (16, 25). During this process, two independent raters (1 physiotherapist, 1 movement scientist) observed the animated stick figures of the reconstructed markers and described the general movement they observed. Based on consensus the final description of the PM was given.

3 Results

3.1 Performance

There was no significant difference in jumping performance between (1) the ACL injured legs and the control group and (2) between injured legs and the contralateral, uninjured legs of the ACL group (see table 2).

3.2 Single-joint alterations

If a parameter significantly increased (or decreased) in amplitude in three tasks or more, then this change was seen as a task-independent alteration. The absolute value and timing-aspects (e.g. the shape of the t-curve) were not required to be exactly the same as this mainly depends on the task requirements. Here we present task-independent alterations only. The detailed results of all biomechanical and neuromuscular parameters can be found in Supplemental Digital Content 2 (figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns).

Increased hamstrings activation

During all tasks, HM and HL activation was higher in the ACL injured legs compared to both the control group and the uninjured legs. Differences were larger in HM (figure 1) than in HL (figure S2.15, Supplemental Digital Content 2, figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns). We found that during the single leg hop 17 of the 21 athletes with ACLR showed larger HM activation in their injured leg compared to the average HM activation of the control group (other tasks: medial hop 19/21 athletes with ACLR, lateral hop 18/21, vertical hop 90° medial rotation 18/21, vertical hop 90° lateral rotation 20/21). Furthermore, 15 of the 21 athletes with ACLR showed larger HM activation in their injured leg compared to their uninjured leg (other tasks: medial hop 17/21 athletes with ACLR, lateral hop 18/21, vertical hop 90° medial rotation 18/21, vertical hop 90° lateral rotation 18/21).

Decreased knee flexion moments

The ACL group had significantly lower external knee flexion moments in their injured leg compared to their uninjured leg during the peak loading phase of all tasks (medial hop 53-210ms, p<0.001; lateral hop: 101-141ms, p=0.0125; vertical hop 90° medial rotation 90-137ms, p=0.0056; vertical hop 90° lateral rotation 85-240ms, p<0.001; single leg hop: trend) (figure 2). We found that during the medial hop 17 of the 21 athletes with ACLR showed lower peak external knee flexion moments in their injured leg compared to their uninjured leg (other tasks: lateral hop 14/21, vertical hop 90° medial rotation 15/21, vertical hop 90° lateral rotation 16/21, single leg hop 15/21 (trend)). No significant differences were found between the ACL injured legs and the control group, except during the single leg hop for distance where the ACL injured legs showed a larger knee extension moment compared to the control group just after IC (26-35ms, p=0.044).

Decreased hip adduction moments

Hip adduction moments were lower in the ACL injured group compared to the control group during the peak loading phase of all tasks (single leg hop 54-75ms, p=0.0251; medial hop 94-102ms, p=0.0477; lateral hop 75-173ms, p<0.001; vertical hop 90° lateral rotation 75-116ms, p=0.0113; vertical hop 90° medial rotation: trend) (fig.S2.2, Supplemental Digital Content 2, figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns).

Decreased knee abduction angles

During all tasks knee abduction angles were smaller in the ACL injured legs compared to the control group, mostly during the entire landing phase (single leg hop 0-50ms, p=0.03 & 70-500ms, p<0.001; medial hop 0-15ms, p=0.048 & 33-499ms, p<0.001; lateral hop 208-277ms, p=0.020; vertical hop 90° medial rotation 0-64, p=0.028; 110-129ms, p=0.048 & 192-500ms, p<0.001; vertical hop 90° lateral rotation 0-500ms, p<0.001) (figure S2.10, Supplemental Digital Content 2, figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns).

Increased pelvis-thorax flexion angles

During the single leg hop for distance, the medial hop and the lateral hop increased pelvis-thorax flexion angles were found in the ACL injured legs compared to the control group (single leg hop: 0-46ms, p=0.0482; medhop: 0-145ms, p=0.0324; lathop: 0-500ms, p<0.001) (fig.S2.6, Supplemental Digital Content 2, figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns).

3.3 Changes in whole-body movement

Some PMs were significantly different 1) between the two legs of the athletes with ACLR or 2) compared to the control group. These differences were all task-specific (figure 3).

When the athletes with ACLR performed the single leg hop for distance on their injured leg they showed a more pronounced posterior movement of their pelvis (figure 3A) (this was found in 14 out of the 21 athletes with ACLR) and a less pronounced whole-body anterior displacement (by reducing the ankle pendulum movement) than when jumping on their uninjured leg (figure 3B) (found in 17/21 athletes with ACLR).

During the vertical hop with 90° of lateral rotation, the ACLR group showed decreased whole-body lateral sway compared to the control group (figure 3C) (found in 15/21 athletes with ACLR).

During the medial hop the ACLR group showed a reduced flexion motion in the ankle joint (figure 3D) (found in 14/21 athletes with ACLR).

No differences in expression of PMs were found in the lateral hop or in the vertical hop with 90° medial rotation.

No differences were found in the first PMs (which described >95% of the total movement variability), but only in the higher PMs which explained less variability of the overall movement. This is to be expected since the lower PMs represent gross movements that determine the primary task demands. These are thus not likely to differ between groups as both groups performed the same tasks. In contrast, the higher PMs describe more detailed and fine movements (e.g. stabilization strategies) and are more likely to be affected by subtle underlying biomechanical differences following ACLR.

4 Discussion

This study found that athletes with ACLR show several task-independent single-joint alterations (between legs, but also compared to uninjured athletes) at the time of RTS, while changes in the whole-body movement were task-dependent. Our hypothesis that single-joint compensations were associated with changes in whole-body movement could thus not be confirmed. For some tasks however, we did find changes in whole-body movement that could clinically be linked to single-joint compensations, suggesting that the whole-body expression of joint-specific deficits is clearer in certain tasks than others. For example, the single leg hop for distance mainly challenged the participants in the sagittal plane (e.g. highest sagittal joint moments of all tasks) and led to changes in whole-body movement in the sagittal plane. In contrast, the vertical hop with 90° lateral rotation, a task that was also challenging in the frontal plane, led to frontal plane alterations.

The most prominent single-joint alteration was the increase in hamstrings activation in the injured leg of the ACL group compared to the contralateral leg and control group. So far, this increased hamstrings activation has not yet been found in other studies that assessed muscle activation alterations after ACL, but is a commonly reported strategy in patients with ACL deficiency (e.g. no reconstruction) (27–29). Increased co-contraction of the hamstrings muscles seems protective as the hamstrings have a posterior line of pull in a flexed knee and might thus act as an ACL agonist, counteracting high anterior tibial shear forces(30–33). In search of changes in whole-body movement that could be associated with this single-joint compensation, one could expect a more erect landing pattern as landing studies showed that landing with decreased knee and hip flexion angles involve more hamstring activation(34, 35). The PCA could not reveal such erect landing pattern in the injured leg, except for the decrease in ankle flexion motion found during the medial hop. Therefore, other mechanisms possibly cause increased hamstrings activation. For example, incomplete recovery of the semitendinosus muscle (all athletes with ACLR underwent a reconstruction using a semitendinosus autograft) may make the hamstrings less effective in force generation which would need to be compensated with larger activation levels (36). Another factor might be rehabilitation as patients often learn to consciously activate their hamstrings to increase co-contraction, especially in the early stages of rehabilitation, to improve knee joint stability. Furthermore, strength training can lead to increased motor unit recruitment and/or firing frequency(37). However, if this were the case, then also alterations in muscle activation in the contralateral leg would have been noticed as strength training was performed on both legs. Finally, increased hamstrings activation might represent an arthrogenic muscle response (AMR), a natural mechanism of reflex facilitation and/or inhibition of muscle surrounding an injured joint to prevent potentially detrimental movements (38, 39). Facilitation of the hamstrings might protect the knee joint as modeling studies showed that increased hamstrings forces were related with reduced anterior tibial shear forces (31–33). However, it is important to mention that muscle activation and forces are not linearly related due to the complexity of activation dynamics and force-length-velocity properties (43), as well as the effects of graft harvesting and injury-related strength deficits. Therefore, the facilitation of hamstrings may not provide the protection of the knee joint that modeling would predict.

Another single-joint compensation observed across tasks, was the decrease in external knee flexion moments in the ACL injured knees compared to the contralateral, uninjured knees. This might again be a protective strategy as high external knee flexion moments are associated with increased anterior tibial shear forces(40), increased ACL loading (41), and even increased primary ACL injury risk(42). Previous studies that investigated landing asymmetries after ACLR(12, 13) also found reduced knee flexion moments and suggested that athletes with ACLR reduce sagittal plane loading in their injured knee by increasing hip/and or trunk flexion to move their center of mass (and thus the GRF) more anteriorly, resulting in smaller moment arms to the knee joint (12, 13). Whilst we indeed found increased pelvis-thorax flexion angles in 3 out of the 5 tasks, the PCA did not reveal task-independent compensations that lead to a more anterior center of mass position. Only during the single leg hop for distance, we found that the athletes with ACLR had a more anterior whole-body position around peak loading when landing on their injured leg compared to landings on their uninjured leg. The absence of difference for the other tasks is possibly due to the less demanding nature of those tasks in the sagittal plane.

A third task-independent single-joint alteration was the decreased hip adduction moments in the ACL injured legs compared to the uninjured legs and control group. As far as we are aware of, this has not yet been found by other studies assessing changes in landing kinetics following ACLR. Only during the vertical hop with 90° of lateral rotation, the PCA revealed less lateral whole-body lean around peak loading which could be associated with this single-joint alteration. This might be a strategy to reduce frontal (hip) joint loads by aligning the GRF with the (hip) joint center, but it remains unclear why that is not the case in any of the other tasks.

Finally, the athletes with ACLR showed decreased knee abduction angles in the injured knees compared to the control group. This might again be a protective strategy as increased knee abduction angles have been associated with ACL injury risk(43). However, since this has not yet been found in other studies, these explorative results should be confirmed by other studies. The reduced knee abduction angles could not be related to any of the whole-body alterations and are most likely related to the increased hamstrings co-activation in the ACL injured knees as the hamstrings play a crucial role in limiting frontal plane motion and frontal plane loading of the knee(44).

Clinical implications

One of the main reasons why we investigated whether single-joint compensations were associated with changes in whole-body movement, was to make screening and rehabilitation easier since the whole-body expression is probably a closer representation of what physiotherapists can observe during screening and rehabilitation. Since a consistent link between the single-joint compensations and changes in the whole-body movement was not found and the fact that whole-body expression largely depends on task requirements, we advise clinicians to measure task-independent single-joint alterations as they are more likely to occur across a broad range of sport- and daily-life activities.

Most single-joint alterations (i.e. increased hamstrings activation, reduced knee flexion moments and reduced knee abduction angles) are likely protective in the short term as they may enhance knee stability and/or reduce sagittal plane loading of the knee joint(31, 45). However, whether they are positive adaptations in the long term, is still doubtful. First of all, we found that athletes with ACLR reduce sagittal plane loading of the injured knee, resulting in asymmetrical knee flexion moments which has been shown to be associated with increased re-injury risk in athletes who underwent ACLR(7). Furthermore, we found high hamstring activation, which might lead to increased knee joint compressive forces(8, 30) and thus increased risk for early development of posttraumatic knee OA (PTOA). Future studies should thus further assess the effect of altered landing patterns on the development and progression of PTOA.

Important to mention is that the single-joint alterations might represent pre-existing deficits that may have increased the risk to sustain the primary ACL injury and that remain present or might even be amplified after the ACL injury(46). For example, we found that the uninjured legs of the ACL group have larger knee flexion moments compared to the injured group but also compared to the control group. It is possible that, before the ACL injury, the injured leg showed high knee flexion moments, similarly to the uninjured legs, as this is a risk factor for primary ACL injury(47). We suggest future longitudinal studies to clarify if knee flexion moments in the injured knee are reduced because of the injury and/or rehabilitation, or whether the asymmetry in knee flexion moments already exists before the ACL injury.

Limitations

This study comes with some limitations. As far as we know, this is the first study that uses marker-based PCA to assess changes in whole-body movement during in athletes with ACLR during landing tasks. Although this technique allows for visualizing key movement coordination patterns, it also involves a degree of subjectivity for qualitative descriptions of each PM. To minimize rater bias, qualitative assessment of the PMs was, therefore, done by 2 independent raters. To improve the objectivity of this approach, future studies should explore if PM joint kinematics and kinetics can be quantified to objectively describe individual PMs. Furthermore, this is an explorative study (without correction for multiple testing) and thus the findings need to be confirmed by other studies that use pre-specific hypotheses and/or corrections for multiple testing (22, 23). Finally, since we did not match the groups for skill level, this might have influenced our results as some participants might have been exposed to landing and/or jumping training in the past or practiced one or multiple of the landing tasks during their rehabilitation.

Conclusion

In conclusion, this study found that athletes with ACLR still show protective task-independent single-joint alterations during single leg landings at the time of RTS. However, marker-based PCA revealed changes in whole-body movement that were dependent on the task. Whole-body representations of the single-joint compensations are thus probably affected by the demands of the task.

ACKNOWLEDGEMENT

This research received no specific grant from any funding agency in the public, commercial, or non-profit sectors.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

The results of the study do not constitute endorsement by ACSM and are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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Supplemental digital content 1

Document that describes the marker)based PCA approach used to assess global compensation strategies

Supplemental digital content 2

Figures with detailed results of kinetics, kinematics, GRF and muscle activation patterns

Figure captions

Fig. 1. Upper row: average HM activation in the ACL injured legs (red), ACL uninjured legs (blue) and control group (black) during the landing phase (from 100ms prior IC until 400ms after IC) of the 5 tasks. Standard deviation clouds are represented by the shaded zones. Lower rows: SPM output of the unpaired t-test (middle row) and paired t-test (lower row). If the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) significant differences were found between groups or between legs, respectively.

Fig. 2. Upper row: average knee flexion moment in the ACL injured legs (red), ACL uninjured legs (blue) and control group (black) during the landing phase (from IC until 500ms after IC) of the 5 tasks. Standard deviation clouds are represented by the shaded zones. Lower rows: SPM output of the unpaired t-test (middle row) and paired t-test (lower row). If the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) significant differences were found between groups or between legs, respectively.

Fig.3: Visualization of the PMs that were different between groups during the landing phase of the different tasks. The graphs in the first column are the time evolution curves (PM scores) of the significant PMs. The stick figures in the second column represent the PMs. To visualize the PMs we plotted the mean posture of the control group at 2 different time points, t1 & t2 (e.g. extremes of the PM scores). The last column visualizes the differences between groups at the indicated time point. A scaling factor (a) was used to exaggerate the differences for visualization purposes in this column.

Furthermore we reported for each retained PM the percentage of variance of the movement that was explained (Expl.Var.) by the PM.