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Original Article

Time course of biomechanics during jump landing before and after two different fatigue tasks

Makoto Asaeda [a,b,*], Kazuhiko Hirata [a], Tomoya Ohnishi [b], Hideyuki Ito [b], So Miyahara [b], Koki Fukuhara [a], Yuki Nakashima [a], Yoshitaka Iwamoto [a], Kai Ushio [c], Yukio Mikami [c], Nobuo Adachi [d]

[a] Division of Rehabilitation, Department of Clinical Practice and Support, Hiroshima University Hospital, 1-2-3, Kasumi, Minami-ku, Hiroshima, 734-8551, Japan
[b] Faculty of Wakayama Health Care Sciences, Takarazuka University of Medical and Health, 2252 Nakanoshima, Wakayama, 640-8392, Japan
[c] Department of Rehabilitation Medicine, Hiroshima University Hospital, 1-2-3 Kasumi, Hiroshima, 734-8551, Japan
[d] Department of Orthopaedics Surgery, Graduated School of Biomedical and Health Sciences, Hiroshima University, 1-2-3 Kasumi, Hiroshima, 734-8551, Japan

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ABSTRACT

Objective: Muscle fatigue contributes to anterior cruciate ligament (ACL) injuries, with increased knee and hip abduction observed during fatigue. However, there have been no reports revealing the differences between fatigue tasks or the duration of these changes. In this study, we conducted single-leg drop landings before and after hip and knee fatigue tasks to elucidate the changes in lower limb biomechanics over time.

Methods: Twenty-two male participants performed single-leg drop landings before, immediately after, and 5, 10, and 15 min after fatigue tasks involving isokinetic hip abduction/adduction (hip fatigue task [HFT]) and knee extension/flexion (knee fatigue task [KFT]). Hip and knee kinematic and kinetic data were collected using a three-dimensional motion analysis device and two force plates. A two-way ANOVA was performed with both the fatigue task (HFT and KFT) and time point (Time 1 to Time 4) as factors, and the main effects and interactions were calculated.

Results: The knee adduction angle after the HFT was significantly greater than that after KFT immediately following the fatigue task. The knee flexion moment was significantly lower in the KFT, whereas the knee adduction and internal rotation moments were significantly higher in the HFT immediately after the fatigue task.

Conclusion: This study revealed distinct kinematic and kinetic changes specific to each fatigue task, particularly in the frontal plane for hip joint tasks and the sagittal plane for knee joint tasks. These findings could assist in the development of ACL injury prevention programs tailored to the functional improvement and exercise capacity of each joint.

1. Introduction

Anterior cruciate ligament (ACL) injuries are caused by knee internal rotation and abduction motion during landing,[1,2] and 8° knee abduction during a double-legged landing has been reported to predict anterior cruciate ligament injury risk.[3] In a meta-analysis by Benjaminse et al.,[4] various factors were shown to cause ACL injury, and fatigue was shown to be a factor associated with ACL injuries. Hawkins et al. showed that sports injuries occurred during the final 15 min in both the first and second halves in competitive football matches.[5] Another study showed that although the total number of injuries was high in the first half of the game, tackling and charging, which cause major injuries, were high in the second half of the game, reflecting muscle fatigue.[6] In a field study that examined ACL injuries and fatigue levels, a higher fatigue level immediately before ACL injury, was shown to be associated with a greater percentage of complete ruptures.[7] The theory behind ACL injuries due to fatigue is as follows: Due to continuous muscle contraction during competition, athletes lose sufficient shock absorption ability, leading to knee abduction,[3] which poses the risk of ACL injury.[8] Previous study[4] examined certain peripheral fatigue tasks that induced

* Corresponding author. 1-2-3 Kasumi, Minami-ku, Hiroshima, 734-8551, Japan.
E-mail addresses: asaedam@hiroshima-u.ac.jp (M. Asaeda), hiratakz@hiroshima-u.ac.jp (K. Hirata), t.ohnishi@tumh.ac.jp (T. Ohnishi), h-ito@tumh.ac.jp (H. Ito), s-miyahara@tumh.ac.jp (S. Miyahara), kouki@hiroshima-u.ac.jp (K. Fukuhara), ynakashi@hiroshima-u.ac.jp (Y. Nakashima), iwamo10@hiroshima-u.ac.jp (Y. Iwamoto), ushiosista@gmail.com (K. Ushio), yukio.liebe@gmail.com (Y. Mikami), nadachi@hiroshima-u.ac.jp (N. Adachi).

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dynamic knee valgus (DKV), focusing on the hip and knee joints involved in posture control during jump-landing. The physiological processes that can cause fatigue are classically divided into two domains: the activation level of the muscle (central) and the other influences on contractile function (peripheral).[9] Fatigue is also classified as perceived or performance fatigability, and it is determined by a wide variety of factors. Peripheral fatigue includes neuromuscular function, metabolism, contractile apparatus, and contraction coupling in peripheral muscles, which is related to fatigue as a task dependency.[9,10] A previous study used electromyography (EMG) and reported that the hip abduction moment in healthy females is reduced by 27 % owing to the weakening of the gluteus medius.[11] Fatigue in the quadriceps and hamstrings is known to significantly increase the knee extension and external rotation at the peak vertical ground reaction force (vGRF).[12] Therefore, lower biomechanical changes due to fatigue accumulation would be considered a risk factor for ACL injury, and it is necessary to examine not only the general fatigue protocol, such as that reported in previous studies, but also the differences observed in the peripheral fatigue protocol by focusing on the joints of the lower limbs. However, systematic reviews have reported that kinematics and kinetics data from the fatigue tasks are not consistent. Moreover, only a few studies have investigated the biomechanics of lower limbs considering different tasks.[13]

About the effect of elapsed time after fatigue, a previous study reported that the increase in knee abduction moment and internal rotation angle during cutting motion continued even after 40 min of 50 % of maximal vertical jump followed by a 30-m sprint.[14] However, the temporal changes in the lower limb biomechanics after different fatigue tasks are not yet clear. By examining the changes over time in lower limb biomechanics after fatigue with different tasks, the usefulness of an injury prevention program that focuses on the lower joint and time to recovery from fatigue was demonstrated. Therefore, regarding changes in lower limb biomechanics due to fatigue, 1) there has been no comparison between different fatigue tasks, and 2) there are few reports on changes over time. By investigating these aspects, we will be able to determine which fatigue tasks are likely to cause knee valgus, a risk factor for ACL injury, and how long it takes for these changes to manifest. This study will contribute to establishing a scientific basis for the effects of selective muscle-strengthening training on ACL injury prevention and fatigue prevention.

Therefore, this study aimed to assess single-leg drop landing before and after hip and knee fatigue tasks, to clarify the changes in lower limb biomechanics over time. The fatigue task focused on the knee and hip joints that are involved in the posture of the ACL injury,[1,2] and two fatigue tasks were compared: knee fatigue task (KFT) and hip fatigue task (HFT). The hypothesis is that hip abduction and knee abduction increase after both hip and knee fatigue tasks, and the change continues until 15 min after the end of the fatigue task since it takes 15 min for muscle exertion and blood lactate to recover from the abrupt immediate changes after functional fitness strength training.[15] In addition, evidence suggests that neuromuscular training focusing on hip joint function is effective in preventing ACL injury,[16] and decreased strength in hip abductors is a potential factor predisposing to knee valgus during single-leg landing.[17] HFT was more likely to induce knee valgus than the knee joint fatigue task.

2. Materials and methods

2.1. Participants

This was a single-center study with a prospective single group, and a repeated-measures study was performed on a single campus. Healthy adult males volunteered to participate in the study after viewing a recruitment advertisement poster in a public space. (at the campus entrance, between April 2021 to September 2022) Participant recruitment was conducted by posting a poster. This study was conducted with the approval of our institutional research ethics committee and was conducted in accordance with the Declaration of Helsinki. Informed consent to participate was obtained from those who wished to participate. We recruited participants (i) who could understand the study and provide informed consent in writing, (ii) without a history of orthopedic surgery for lower limb neuromuscular disease, (iii) without pain, (iv) without the limited knee range of motion, and (v) who carried out regular sports activities. A questionnaire was administered to prospective participants to confirm their history of orthopedic surgery related to lower limb neuromuscular diseases and determine the presence or absence of pain. Additionally, joint angles were measured using a goniometer to assess individuals with limited range of motion in the lower limb. The exclusion criteria included individuals with a history of orthopedic surgery or lower limb pain, limited joint range of motion (i.e., less than 135° of flexion or a not fully extended knee), maintaining posture when jumping and landing, missing data, not carrying out regular sporting activities, and carrying out sporting activities at the competition level (e.g., professional sports level).

2.2. Single-leg drop landing

The participants wore tight clothes, and 39 infrared reflective markers (diameter: 10 mm) were attached to the whole body in accordance with the Plug-in Gait model of the Vicon Motion System. The jump-landing motion was a left-leg jump-landing motion from a 20-cm height. Before the fatigue tasks, the participants were asked to practice the movement thrice. We adopted a 5-sec duration to maintain a successful landing attitude and asked the participants to perform a successful landing thrice (Remain in the position at the moment of landing for 5 s; flex hip and knee and do not lift upper limb, Fig. 1). No practice was performed for measurements immediately after fatigue. All participants had a history of competing in sports but lacked prior experience in performing the specific jump-landing motion used in this study. During jump landing, data on the marker position and ground reaction force (GRF) were collected using a three-dimensional (3-D) motion analysis device (Vicon MX, Vicon Motion Systems, UK) and a force plate (AMTI, USA). The camera frequency for the 3-D motion analysis was 100 Hz, and the GRF was recorded at 1000 Hz for each force plate. The obtained marker position data were subjected to a 6-Hz low-pass filter (Butterworth fourth-order filter).

2.3. Fatigue task

Two different fatigue tasks (KFT and HFT) were performed on the left lower limb at least 3 days apart, and the measurement order of the fatigue task (Hip or Knee) was determined using simple randomization. Since all participants were right-handed, the left lower limb opposite to the dominant leg was considered as the measured limb. A single-leg drop jump was performed before (Time 0), immediately after (Time 1), and at 5 min (Time 2), 10 min (Time 3), and 15 min (Time 4) after each fatigue task. During the measurement interval after the fatigue task, the participants waited in a standing position. Data was collected in a secure room, ensuring minimal external influence during measurements, which were conducted by two individuals, (MA and HI).

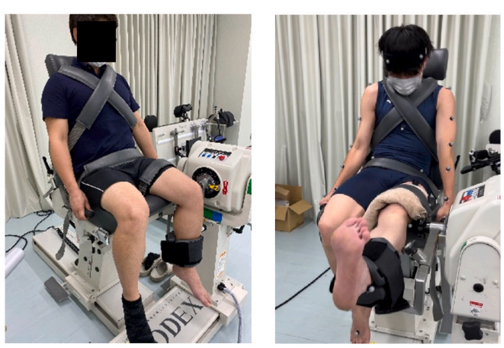
The isokinetic movement was adopted as the fatigue task. Using the Biodex Medical Systems (USA), isokinetic knee extension/flexion movement as the KFT and hip abduction/adduction movement as the HFT was performed by the participants. Muscle torque was recorded during both tasks, and the degree of subjective fatigue was evaluated using the Borg scale. The ratio of objective fatigue was calculated from muscle torque value during the first three attempts and the last three attempts during the fatigue task (% = average value of the last three attempts/average value of the first three attempts). The reasons for choosing these two tasks are as follows: a quantitative measurement method has been reported in BIODEX,[18–20] strength around the knee joint is often used as an evaluation index in the return-to-sports

Fig. 1. A posture of successful landing (Remain in the position at the moment of landing for 5 s; flex hip and knee and do not lift upper limb).

criteria,[21] and training the muscles around the hip joint has been shown to prevent ACL injury.[16] During the fatigue task, the subjects were instructed to always perform the exercise under maximum effort while checking the voice and peak torque value.

The HFT was performed in the right lateral recumbent position with the left lower limb elevated, left hip flexion 0°, and the right hip and knee joints slightly flexed. The participants held the head of the chair and grasped the bar with both upper limbs. The attachment was placed on the distal left thigh (proximal knee joint), and the axis of rotation was aligned with the upper part of the greater trochanter. Gravity correction

A



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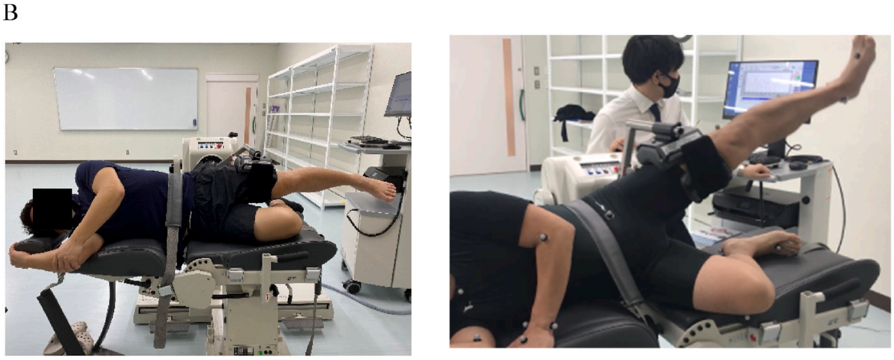

Fig. 2. Positions during the fatigue task. (A) Knee-joint fatigue task (KFT): left.; starting position, right; during task (B) Hip-joint fatigue task (HFT): left.; starting position, right; during task.

of the lower limbs was performed at 30° of hip abduction in the left lower limb. The range of movement was set to 10° hip adduction and 30° abduction, and the angular velocity was set to 60°/s, in accordance with a measurement method that showed good reliability.[18,19] Each abduction-adduction procedure was performed 40 times. An image of the HFT is shown in Fig. 2A. The KFT was performed in a sitting position with the chair tilted at 8° and the participant held the bars of the chair with both upper limbs. The attachment was placed distal to the left lower leg (2 cm proximal to the medial malleolus) and the axis of rotation was aligned with the line connecting the medial and lateral condyles of the femur. Gravity correction was performed at 20° knee flexion. The participants performed a knee joint extension movement with maximum effort from 135° knee joint flexion and then performed flexion with maximum effort when reaching °0 extension. Referring to previous research that confirmed the good reliability of the test, we set the angular velocity at 120°/s and the number of movements at 40, each.[20] The KFT is shown in Fig. 2B.

2.4. Data analysis

Data were analyzed at the data collection site by a single individual using a computer with no Internet connectivity. The analyzed results were reviewed by two individuals, TO and SM, to ensure their validity. Lower limb kinematics and kinetics were calculated using the Plug-in Gait model using NEXUS 2 (Vicon MX, Vicon Motion Systems, UK) from the obtained marker position data and GRF during the landing task. We obtained the hip and knee kinematic and kinetic data, including the lateral, anteroposterior, and vertical components of the GRF at the vertical GRF max (peak vGRF) in each time point (Time 0 to Time 4). To consider individual differences, the amount of change was calculated based on the value at Time 0. In addition, we calculated the change in the pelvic angle and peak vGRF for the kinematic explanation. During the fatigue task, the percentage value (degree of objective fatigue) was obtained by dividing the peak muscle torque from the start of the movement by three times that from 37 times to the end of movement. The peak torque of knee joint extension was recorded in the KFT and that of hip abduction in the HFT. All joint angles and joint moment values were used at peak vGRF.

2.5. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 27 (IBM Japan, Japan). The number of participantss was selected based on a previous meta-analysis[4] that showed significant differences in the peak hip flexion angle during single-leg landing. From their survey, we chose a study[22] that investigated the effect of lower fatigue on lower biomechanics, used to detect a sample size with a significance level of 5 %, power = 0.8 in G power 3.1.9.4 (Program written, concept, and design by Franz, Universitat Kiel, Germany.). The required sample size was calculated to be 21 (Hip flexion angle before fatigue task, 32.5 ± 13.2; after fatigue task, 43.7 ± 19.7). Similar to the present study, a previous study[22] measured kinematics and kinetics during single-leg jump landings before and after a fatigue task in healthy males.

A Two-way ANOVA with repeated measures was performed with both the fatigue task (HFT and KFT) and time point (Time 1 to Time 4) as factors, and the main effects and interactions were calculated. When an interaction was observed, a Bonferroni multiple comparison test was used. The significance level was set at $p < 5$ %.

3. Results

3.1. Participants

Twenty-four males wanted to participate in the study. However, one had pain during jump landing, one was unable to make a stable landing during the practice phase before the fatigue task, and one had a history of lower leg fracture in the past year from the questionnaire (This questionnaire was to confirm the history of orthopedic surgery related to lower limb neuromuscular diseases and determine the presence or absence of pain.) before the landing task; hence, they were excluded. Finally, the total participants were 21 healthy male adults with no history of orthopedic surgery in the lower limbs (mean age, 19.9 ± 0.9 years; height, 173.0 ± 6.5 cm; weight, 66.0 ± 10.4 kg). The sports activity level of all participants was at the recreational level, and none participated at the competitive level, according to the questionnaire.

3.2. Degree of fatigue

After the HFT, the median degree of objective fatigue (average value of the last three attempts/average value of the first three attempts) was 41.3 ± 9.9 %, which was significantly different from that after KFT (52.2 ± 11.4 %; $p = 0.003$). The degree of subjective fatigue showed a significant difference between the two groups (after HFT: 16.0 points [median, interquartile range; 15.0–17.0], KFT: 17.0 points [16.0–18.5], $p = 0.024$).

3.3. Time course of lower limbs kinematics and kinetics

3.3.1. Main effect

There was a main effect of time in the hip internal rotation angle, and it decreased significantly at Time 1 compared to Time 0 in both tasks (Fig. 3F, Supplemental 1).

3.3.2. Interaction

In kinematics, there was a significant interaction in the knee adduction angle, which increased immediately after the HFT (Time 1) and was significantly higher than that at Time 0 and Time 4 (Fig. 3B, Supplemental 1). In terms of kinetics, the hip flexion moment at Time 1 of the KFT was significantly higher than that at Times 0 and 4 (Fig. 4D, Supplemental 2). In the HFT, the hip adduction moment at Time 1 was higher than that at Times 3 and 4 (Fig. 4E, Supplemental 2). There was a significant interaction in the knee adduction moment, which was significantly higher than Time 0 at Time 1 and Time 2 in the HFT (Fig. 4B, Supplemental 2). The knee internal rotation moment showed an interaction, and the increase in the internal rotation moment was significantly higher at Time 1 than at Time 0 and 4 in the HFT. In KFT. It was significantly higher at Time 4 than at Time 0.

3.4. Comparison between HFT and KFT

3.4.1. Kinematics

In Time 1, the knee adduction angle after HFT was significantly greater than that after KFT (Fig. 3B, Supplemental 1). Regarding the pelvic rotation angle, a significant main effect was observed, and the HFT showed significantly greater pelvic right rotation than the KFT (Fig. 5B, Supplemental 1).

3.4.2. Kinetics

Compared to the HFT, the hip adduction moment in the KFT was higher at Times 1 and 2 (Fig. 4E, Supplemental 2). A significant main effect of the fatigue task on peak vGRF was observed, and the HFT group showed significantly greater vGRF than the KFT group (Fig. 5A, Supplemental 2). The knee flexion moment showed a main effect of the task and was significantly lower in the KFT (Fig. 4A, Supplemental 2). Knee adduction and internal rotation moments at Time 1 were significantly higher in the HFT group than in the KFT group (Fig. 4B and C, Supplemental 2).

4. Discussion

Since it takes 15 min for muscle exertion and blood lactate to recover from the immediate changes following functional fitness strength

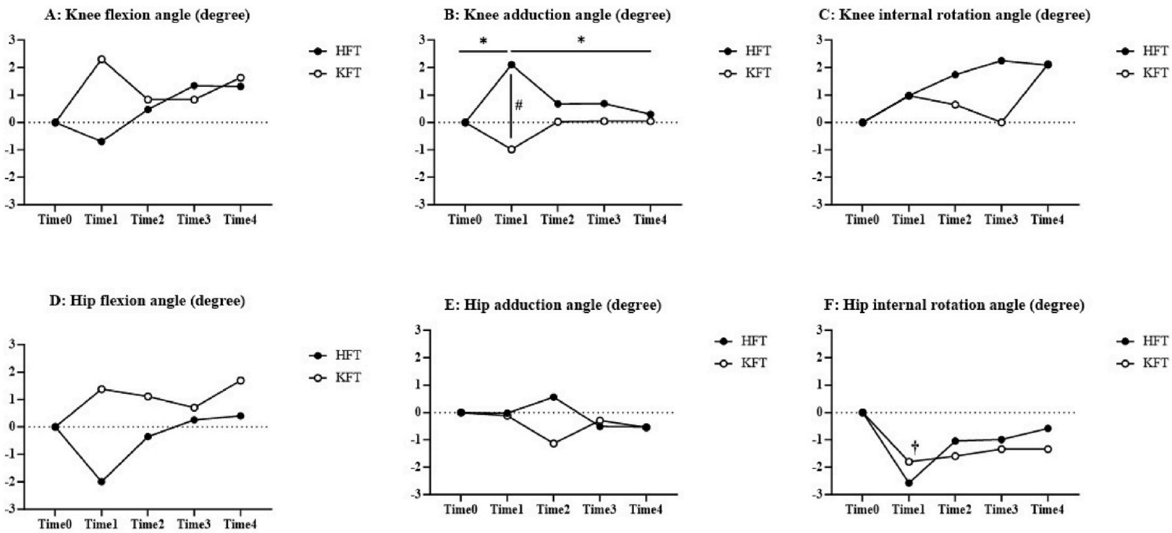

Fig. 3. Time course of kinematics change in hip and knee HFT: hip fatigue task; KFT: knee fatigue task; A: Knee flexion angle. B: Knee adduction angle. C: Knee internal rotation angle. D: Hip flexion angle. E: Hip adduction angle. F: Hip internal rotation angle. *: Significant interaction in HFT between at Time 1 and Time 0, Time 4. #: Significant differences between HFT and KFT at Time 1. †: A main effect of time between Time 0 to Time 1.

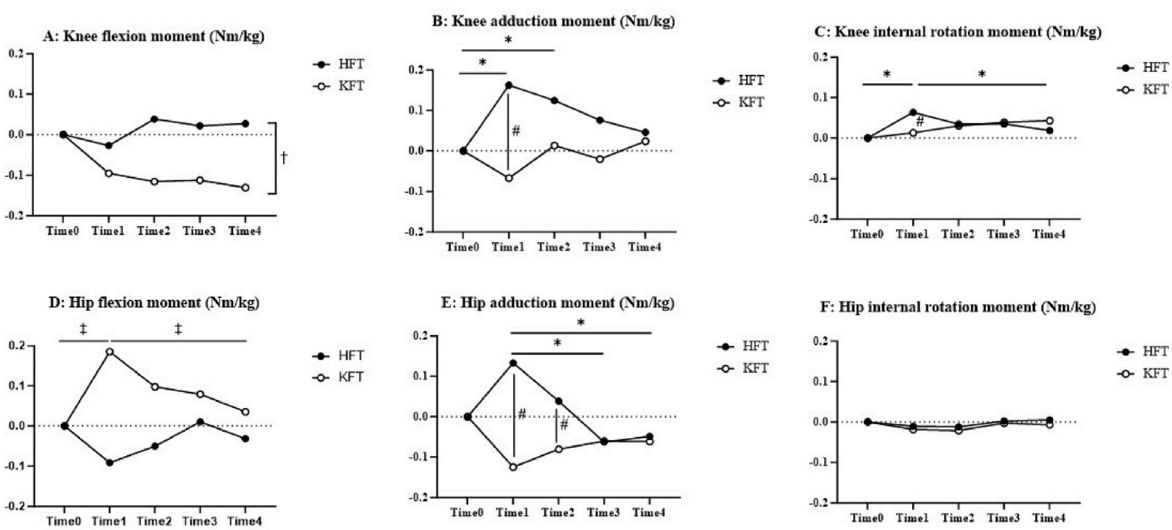

Fig. 4. Time course of joint moment in hip and knee
HFT: hip fatigue task; KFT: knee fatigue task; A: Knee flexion moment. B: Knee adduction moment. C: Knee internal rotation moment. D: Hip flexion moment. E: Hip adduction moment. F: Hip internal rotation moment. *: Significant interaction in HFT. #: Significant differences between HFT and KFT. †: A main effect of time between HFT to KFT. ‡: Significant interaction in KFT.

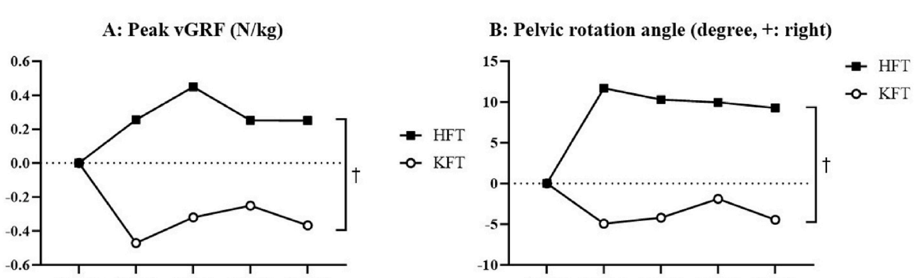

Fig. 5. Time course of peak vGRF force and pelvic rotation angle
HFT: hip fatigue task; KFT: knee fatigue task; vGRF: vertical ground reaction force; A: Peak vGRF B: Pelvic rotation angle. †: A main effect of time between HFT to KFT.

training, the hypothesis was that hip abduction and knee abduction would increase following both hip and knee fatigue tasks, and that these changes would persist until 15 min after the fatigue task. In our study, both HFT and KFT showed changes in hip and knee joint biomechanics during jump landing immediately after the fatigue task. The result indicates a significant increase in the knee adduction angle immediately after HFT. Furthermore, a significant difference was observed between the two tasks at Time 1. This suggests that the knee adduction angle increases more after HFT compared to KFT, and this abnormal behavior disappears by 15 min (Time 4). The pelvic rotation angle, peak vGRF, and knee joint flexion moment showed the main effects between tasks, and the effects differed depending on the type of fatigue task. Additionally, in both fatigue tasks, the hip internal rotation angle significantly decreased immediately after the task. Our fatigue task is a method based on previous research, and the degree of peak torque reduction in BIODEX was 41.3 % and 52.2 % for HFT and KFT, respectively, and the decreasing muscle torque is also consistent with previous research.[11] However, there was no significant increase in hip/knee abduction (both angles and moments) in either HFT or KFT. Consistency has been inconsistent with respect to knee adduction angle and the moment after fatigue tasks,[4] Kernozek et al. reported that the increase in knee adduction angle and internal knee abduction moment after performing a limited number of squats was higher than that before the fatigue task, especially in males.[23] These results suggest that there is a sex difference in the occurrence of hip and knee abduction when the exercise is performed with an equal load as a fatigue task. Females generally have a larger knee abduction angle (smaller adduction angle) than males during the dynamic task.[24] The sex difference has been reported to continue even after the fatigue task.[23,25] Therefore, it is important to clarify sex differences in whether hip abduction and knee abduction are caused by fatigue. We clarified that muscle fatigue around the hip joint did not cause a decrease in the increase in knee abduction moment in males. HFT increased the knee adduction angle and moment but did not change the hip adduction angle or decrease the hip internal rotation angle. A previous report showed that the internal hip rotation angle was higher after performing an isokinetic hip internal/external task.[26] The main contraction muscle in this study was the gluteus medius, the activity of which increased with internal rotation of the hip joint.[27] Thus, it is possible that the femur was externally rotated owing to fatigue of the medialis muscle. In addition, since the pelvis rotates to the right in HFT, it is thought that the fatigue of the muscles around the hip joint made it difficult to control the pelvic movement, causing the femur to rotate relatively externally and increasing the knee's internal rotation moment. Since the knee internal rotation moment is closely related to the knee adduction moment,[28] it is thought that the knee adduction moment increases with pelvic rotation during HFT. In KFT, the fatigue task decreased knee extension moment and increased hip flexion moment. It is inferred that this is caused by the compensatory movements of the muscles around the knee joint. Previous studies have reported the possibility of compensatory movements in the hip and knee joints in the fatigue task of the quadriceps alone or the fatigue task of the lower extremity.[29,30] Since the knee extension moment is attenuated in KFT, the increase in the hip joint flexion moment and the decrease in peak vGRF are also compensatory movements similar to those in previous studies.[30] A previous meta-analysis showed that included a bilateral drop jump task reported that the peak vGRF at jump landing after a fatigue task decreased; however, there was no change when limited to a single-leg drop jump.[31] In this study, KFT decreased peak vGRF and HFT increased it. This suggests that the peak vGRF after the fatigue task affected the type of fatigue task. Our second aim of the study was to determine whether there is a time-varying difference between the HFT and KFT. The increase in knee adduction angle and moment during the HFT was significantly higher 15 min after the fatigue task than immediately after the fatigue task. On the other hand, in the HFT, the increase in right pelvic rotation was consistently higher immediately after exercise, and compensatory movement in the pelvis was sustained for 15 min after the fatigue task. It was suggested that the effects of muscle fatigue in the hip abduction/adduction fatigue task continued for more than 15 min after exercise. Previous studies have shown that the increase in knee abduction moment during cutting by a whole-body fatigue task persists for 40 min after the task,[14] and it has been reported that postural control after knee and hip eccentric extensor exercises decreases for 15 min after exercise and recovers after 30 min.[32] Furthermore, there are reports that the peak torque before and after instantaneous training normalizes in 20 min,[33] The advantage of this study is that the changes in kinematics and kinetics due to uniform exercise may normalize within 15–20 min. In addition, the decrease in knee flexion moment and peak vGRF in the KFT was constant for 15 min after the isokinetic hip flexion/extension exercise, suggesting that sagittal biomechanics may not normalize even after 15 min. In this study, we could not directly obtain the results of direct hip and knee abduction using fatigue tasks; however, we were able to clarify the characteristic kinematics and kinetic changes in each task. An increase in the hip adduction moment in the HFT increases the external force that causes hip adduction, which causes loading on the ACL inury.[34] Therefore, the increase in hip adduction moment obtained in this study may be a precursor factor for hip and knee abduction due to fatigue. In addition, a relationship among pelvic rotation, hip abduction, and knee abduction has been reported,[35] changes in pelvic rotation with increased fatigue may contribute to additional ACL stress on the knee joint. This study, in which a fatigue task was set for each joint, will help clarify the compensatory mechanism leading to the occurrence of hip and knee abduction due to fatigue. Both fatigue tasks required a hip response. This contributes to the scientific basis of the effectiveness of hip training for ACL injuries in a prospective study.[16]

This study has several limitations, including involvement of only male participants, lack of high-level athletes, and inconsistent sports histories. In addition, hip and knee abduction did not occur, and compensatory movements such as increased knee adduction angle and moment occurred. The effects on kinematics and kinetics in the fatigue task are not consistent even in meta-analyses,[4] and it is necessary to investigate different exercise loads on the same participants in the future. A significant difference was also observed between HFT and KFT in terms of the rate of decrease in peak torque and subjective fatigue in BIODEX. Therefore, it is unclear whether the muscles around the joint are equally fatigued, and additional electromyographic analysis is required. Furthermore, regardless of the type of fatigue task, our analysis determined that peripheral fatigue tasks are likely to induce a risk of ACL injuries. In muscle strength training after ACL injury or ACL reconstruction, we often target only the area around the knee joint or evaluate muscle performance without considering factors such as fatigue. We did not measure the bone morphology or alignment of the participants. Previous studies have reported that participants with valgus have shorter vertical jump distances[36]; however, it is not possible to prove that participants with knee valgus are more affected by fatigue. In addition, the participants of this study were young individuals, and the results cannot be applied to elderly people whose muscle strength decreases after a fatiguing task.[37]

5. Conclusion

We performed uniform knee extension/flexion exercises and hip abduction/adduction fatigue tasks, and the kinematic and kinetic characteristics of each task were determined 15 min immediately after the exercise. This study revealed distinct kinematic and kinetic changes specific to each fatigue task, particularly in the frontal plane for hip joint tasks and sagittal plane for knee joint tasks. This research will help devise an ACL injury prevention program based on the functional improvement and exercise capacity of each joint.

Conflicts of interest statement

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Declaration of competing interest

The authors declare no conflicts of interest associated with this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asmart.2024.06.002.

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