Regular Article

Title:

Changes in neurocognitive function after acute high-intensity exercise: Decreasing the biomechanical risk factors of ACL injury

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Running Title: Changes in neurocognitive function

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Abstract: Lower baseline neurocognitive ability could be a risk factor for anterior cruciate ligament (ACL) injuries. We investigated the effects of high-intensity exercise (HIE) on neurocognitive function in athletes, and if any changes in neurocognitive function after the HIE had effects on an unanticipated cutting motion. Fourteen collegiate female athletes performed a bicycle ergometer HIE exercise at 80% of their heart rate reserve. Neurocognitive function was evaluated by the Stroop Interference Test (SIT) pre- and post-HIE. Biomechanical variables were captured using a motion analysis system while participants performed side-step cutting tasks in anticipated and unanticipated conditions. Participants were divided into two groups according to the changes of SIT scores after HIE: increased performers (IP; n = 7) and decreased performers (DP; n = 7). The average SIT score of the IP group significantly increased, while that of the DP group significantly decreased after the HIE (Paired t-test, $P < 0.001$). The main effect of the HIE using repeated-measures ANOVA, was a significant decrease in peak knee valgus moment (pre: anticipated-condition − 0.1 ± 0.1Nm/kg, unanticipated 0.0 ± 0.2Nm/kg; post: anticipated 0.0 ± 0.1Nm/kg, unanticipated 0.1 ± 0.2Nm/kg, $P = 0.024$) and peak ground reaction force (pre: anticipated 3.3 ± 2.1%BW, unanticipated 3.8 ± 2.1%BW; post: anticipated 3.1 ± 3.4%BW, unanticipated 3.6 ± 3.6%BW, $P = 0.035$) only in the IP group. The athletes with improved neurocognitive functions had decreased the biomechanical ACL injury risk factors during the side-step cuttings. Improving neurocognitive function may contribute to ACL injury prevention.

(Word Count: 246, *limited 250)

Keywords: ACL injury, neurocognitive function, anticipation, biomechanics

表題：高強度一過性運動後の神経認知機能の変化：ACL 損傷バイオメカニカルリスクファクターの減少

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和文抄録：
ベースラインの神経認知機能が低値であることは，前十字靭帯（ACL）損傷のリスクファクターである可能性が示唆されている．我々は，高強度一過性運動（HIE）がアスリートの神経認知機能に及ぼす影響と，HIE 後の神経認知機能の変化が非予測的カッティング動作に与える影響を調査した．対象者は，大学女子アスリート 14 名であった．HIE は，自転車エルゴメーターを使用し心拍数予備能の 80%の運動強度にて実施した．HIE 前後の神経認知機能は，ストループ干渉テスト（SIT）によって評価された．予測・非予測的カッティング動作中のバイオメカニカル変数は，三次元動作解析装置を用いて測定した．対象者は，HIE 前後の SIT スコアの変化に基づいて 2 群に分けられた：神経認知機能向上（IP; $n = 7$）群と減少（DP; $n = 7$）群．HIE 後，IP 群の平均 SIT スコアは有意に増加し，DP 群の平均 SIT 得点は有意に減少した（Paired t-test, $P < 0.001$）．二元配置分散分析の結果では，IP 群においてのみ，膝関節の最大外反モーメント（HIE 前：予測条件 −0.1 ± 0.1Nm/kg，非予測条件 0.0 ± 0.2Nm/kg；HIE 後: 予測条件 0.0 ± 0.1Nm/kg，非予測条件 0.1 ± 0.2Nm/kg，$P = 0.024$）と最大地面反力（HIE 前：予測条件 3.3 ± 2.1%BW，非予測条件 3.8 ± 2.1%BW；HIE 後: 予測条件 3.1 ± 3.4%BW，非予測条件 3.6 ± 3.6%BW，$P = 0.035$）の減少に対して HIE による有意な主効果が認められた．神経認知機能が向上した選手は，カッティング動作中の ACL 損傷バイオメカニカルリスクファクターが減少した．したがって，神経認知機能の向上は，ACL 損傷予防に寄与する可能性が示唆された．

Introduction

Anterior cruciate ligament (ACL) injury is one of the most severe sports injuries for athletes. It leads to considerable short- and long-term problems, including, but not limited to, the decreased length of an athlete's career[1)], high re-injury rates[2)], early development of post-trauma osteoarthritis[3)], and high medical costs[4)]. ACL injuries typically occur during athletic movement such as cutting in a non-contact manner[5),6)]. Furthermore, it has been reported that incidence rates of ACL injury in female athletes are 2–3 times higher than males during the same sports[7)]. Therefore, preventing non-contact ACL injuries during sport and physical activity for female athletes is especially important.

Recently, poor neurocognitive function has been suggested as a new plausible risk factor for non-contact ACL injury[8)–11)]. Swanik et al.[8)] measured neurocognitive function using "ImPACT"; reporting that the non-contact ACL injured group showed lower scores in reaction time, processing speed, and visual/verbal memory. Subsequently, some studies investigated the association of neurocognitive function with biomechanics during unanticipated motion[9)–11)]. Herman et al.[9)] reported that athletes with lower neurocognitive performance demonstrated knee kinematic and kinetic patterns that are linked to ACL injury. In most cases, non-contact ACL injuries have been observed to occur under multitasking and unanticipated situations[12),13)]. Processing of multiple tasks reduces motor capabilities, and thus, could induce biomechanical stability deficits14),15). Therefore, neurocognitive function could play an important role in decision making and motion execution in unanticipated situations.

Although many studies have proved that neurocognitive function is altered by acute exercise16)–21), past studies8),9),22) that examined the relationship between neurocognitive function and ACL injury have only assessed neurocognitive function at rest. Particularly during team ball sports, athletes need to perform a high-level of motor-cognitive multitasking under high-intensity loads23),24). Intermittent and repetitive high-intensity physical exertion are required in team sports such as basketball, soccer, and handball23)–25). Therefore, it is necessary to consider any changes in neurocognitive function caused by acute high-intensity exercise (HIE) and to examine the biomechanics during unanticipated motion.

A number of literature reviews19)–21),26) have concluded that moderate-intensity exercise (≈40 to 80 % $\dot{V}O_{2\,\mathrm{max}}$) promotes positive changes in neurocognitive function. On the other hand, a consensus on the effect of HIE (> 80 % maximal power output) on neurocognitive function in athletes has not been reached27),28). For example, some studies have found positive effects29), negative effects18),30)–32), and some no effects33)–35) of HIE on neurocognitive performance in athletes. Thus, future research is needed to clarify the effects of HIE on neurocognitive function in trained populations.

Therefore, this study aimed to examine; (1) the effects of HIE (80 % of heart rate reserve) on neurocognitive function in athletes, and (2) the effects that any changes in neurocognitive function after the HIE have on unanticipated motion.

Materials and Methods

Acute high-intensity exercise (HIE): Definition.

In line with previous reviews an “acute” exercise period was defined as “exercise performed within a single day”19). Consistent with the definitions used by guidelines of the American College of Sports Medicine (ACSM)36), high-intensity exercise was defined as high intensity (80 % heart rate reserve).

Participants.

Participants were 14 collegiate female athletes (mean ± SD age: 19.9 ± 1.6 years; height 1.62 ± 4.9 m; weight: 57.0 ± 4.3 kg). Inclusion criteria were (1) female sex, (2) age older than 18 years, (3) participate in jumping/cutting sports (e.g., basketball, soccer, lacrosse, rugby) in university athletic clubs, and (4) engagement in regular physical activity (training of these sports at least 2–3 hours per day, 5–6 days per week). Exclusion criteria were (1) any current injuries in the lower limbs, (2) concussion within the past six months, (3) any disorder of the peripheral sensory system, (4) a past history of surgery in the lumbar spine or lower limbs, (5) being color-blind, (6) previously taking the Stroop Color and Word Test, (7) taking medication that might affect neurocognitive ability, and/or (8) neurocognitive impairment that would inhibit motor learning. This study was approved by the Ethical Committee of the Faculty of Health and Sports Sciences at the University of Tsukuba (approval number. 020-165) and each participant provided written informed consent before data collection. Participants were required to abstain from alcohol and caffeine consumption for at least 24 hours prior to the experiment, and to get adequate sleep the day before in order to control for external factors that might affect neurocognitive function.

Experimental procedure.

Each participant completed a consent form and questionnaire, and then heart rate (HR) at rest was measured in a quiet room. After that, any anatomical characteristics that could be a risk factor of ACL injury; Q-angle, thigh-foot angle, leg-heel alignment, and navicular drop height37) were collected from the dominant leg. The dominant leg was defined as the leg with which the participants would prefer to kick a ball38). An outline of the experimental procedures is shown in Fig. 1.

The first section of the pre-session was the Stroop Interference Test (SIT) as a neurocognitive test. Before the SIT, sufficient explanation was given to each participant and practice was conducted until the participant became familiar with the SIT, to prevent any change between pre- and post-session due to habituation. We believe that the familiarization phase and the full randomization of the SIT trials reduced the risk of observing a repetition effect.

After the neurocognitive test, participants warmed up with 2 minute jog at a self-selected pace followed by 3 minutes of dynamic quadriceps and hamstrings stretching39). Participants then completed the motor tasks including side-step cutting (CUT), single-leg landing (LAND), and forward stepping (STEP) tasks in unanticipated and anticipated conditions11).

After the motor tasks, participants were seated on a cycle ergometer (Power Max VIII, Konami Corp., Tokyo, Japan) and HIE was performed. The HIE intensity was determined as target heart rate (THR). The definition of THR is given in detail later. During the exercise, the workload and pedal speed were gradually increased until the individual reached the desired THR, based on a previous study16) and our pilot study. The method of gradually increasing workload is explained later. Immediately after reaching the THR, the participants were asked to perform SIT simultaneously as a post-neurocognitive test and to continue pedaling while maintaining pedal speed until the end of the neurocognitive test. Finally, the post-motor task was performed within 1 minute after the end of the HIE.

[Fig. 1 about here.]

Neurocognitive test.

High-order neurocognitive function, which is also referred to as executive function, was tested with SIT[40),41)]. This is a test of how fast the participants can say the colors of the ink words are printed in, ignoring the word that is printed for each item. The participants continued to say the ink colors according to the order of the columns for 45 seconds. The score was calculated as the number of correct responses in 45 seconds. In this study, the participants were divided into two groups. The increased performance (IP) group was participants whose neurocognitive test scores increased post compared to pre, and the decreased performance (DP) group was participants whose neurocognitive test scores decreased post compared to pre. By chance, the scores resulted in two groups with an equal number of participants.

Motor tasks.

Participants performed the motor tasks in the order of unanticipated condition, and then anticipated condition. The motor tasks consisted of three motions in which the participants hopped down to the center of a force plate from a 30-cm-tall box using the dominant leg. The dominant leg was defined as the leg with which the participants would prefer to kick a ball[38)], and the box was placed at a distance of 50 % of their leg length (anterior superior iliac to medial malleolus) away from the center of the force plate. The participants were required to perform one of 3 tasks according to an instruction by a projector screen (KIJ Corporation, Tokyo, Japan) which was set 10 m away from the box. The size of the screen was width 215.4 cm and height 134.6 cm. The instructions for each motor task were: (1) CUT: when a yellow horizontal arrow is displayed, perform a side-step cutting 45 degrees toward the nondominant leg side, (2) LAND: when a blue circle is displayed, perform a single-leg landing, and (3) STEP: when a red upward arrow is displayed, step forward[11)] (Fig. 2).

In the unanticipated condition, the projector screen was synchronized with a footswitch placed on the box, and one of the three instructions was set to display randomly. Participants were asked to stand with their dominant foot on the foot switch and perform the task which appeared on the screen the moment they left the box. Whereas, in the anticipated condition, the instruction was displayed in advance, then the participants performed the task after they sufficiently recognized the task to be performed. The motor tasks were finished when the participants successfully completed each task three times under both conditions. In this study, only the first successful CUT tasks in each session and condition were analyzed.

[Fig. 2 about here.]

Kinematic and Kinetic data collection and processing.

A three-dimensional motion analysis system, the VICON MX motion analysis system (VICON, Oxford, England) was used to capture the task motions with a 250 Hz sampling rate through 12 infrared cameras. Ground reaction force data (GRF) was obtained at 1,000 Hz from a force platform (Kistler Instruments, Inc., model 9281C, Winterthur, Switzerland) which was synchronized with the kinematic data. Thirty-five retroreflective markers were attached to the whole body of each participant in a standard Plug-in Gait model (Helen Hays marker-set) on anatomical landmarks42),43). The participants wore the athletic shoes they normally wear when engaging in sports activities and the motion capture suit. A matched 15Hz fourth-order Butterworth filter was used for the marker and force data[44)]. All kinetic data were normalized to body weight. As described in a previous study[45)], the 'initial contact' (IC) was defined as the time where vertical GRF was higher than 10 N. Peak value was defined as the maximum (joint flexion, adduction (varus), and GRF) or minimum (joint extension and abduction (valgus)) value of any dependent variable between the IC and 100 milliseconds (msec) after the IC because most non-contact ACL injuries occur within 100 msec after the IC[46)]. Furthermore, the difference between the maximum and minimum joint angles from the IC to 100 msec after the IC was calculated as angular displacement.

Acute high-intensity exercise.

A cycle ergometer (Power Max VIII, Konami Corp., Tokyo, Japan) was used for the HIE protocol. At first, a 6 minute warm-up was performed at a low-intensity workload of 0.4 kp and a pedaling speed of 70 rpm[16)]. Following the warm-up phase, the workload was gradually increased by increasing the resistance by 0.1 kp every 30 seconds while maintaining pedal speed at 80–90 rpm until each participant reached the THR. We applied this incremental method because it had allowed participants to maintain pedal speed based on our pilot study. Until the participants could not hold the pedaling speed above 80 rpm, gradual increases in workload were continued. Immediately after the target heart rate was reached, the participants were asked to perform SIT and to maintain the pedal speed and THR until the end of the test16). Workload and pedal speed during the HIE were recorded every 2 minutes excluding the warm-up period, and then the mean of each variable was calculated.

Acute high-intensity exercise intensity manipulation check.

Heart Rate. The heart rate (HR) was measured using the wearable sensors POLAR V800 HR and POLAR H10 (Polar Electro Oy, Kempele, Finland). In the experiment, two HR variables (resting HR and exercise HR) were identified. Resting HR was assessed following a 10-minute sitting rest. Exercise HR was defined as the mean of the HR values assessed at 2 minute intervals during the HIE excluding the warm-up period16).

The target heart rate. The target heart rate (THR) was calculated using the heart rate reserve (HRR)47) which is a common means of establishing a target heart rate for exercise intensity36). HRR was estimated as the difference between the age-predicted maximum HR (207 − 0.7 × age)48) and resting HR. THR was applied with the following formula: [(desired intensity percentage × HRR) + resting HR]. In this study, the desired intensity was chosen as high intensity (80 % HRR) based upon guidelines of the American College of Sports Medicine (ACSM)[36)].

Rating of Perceived Exertion. Borg's rating of perceived exertion (RPE)[49)] is commonly used to assess a participant's subjective perception of exertion during exercise. The rating ranges from 6 to 20, where the values from 6 to 11 are categorized as "no exertion to light," the values from 12 to 14 are categorized as "some exertion," the values from 15 to 20 are categorized as "hard to maximal exertion". The RPE was assessed at 2 minute intervals during the HIE excluding the warm-up period, and then the mean and maximum values were calculated[16)].

Statistical analysis.

All statistical analyses were performed using SPSS statistics 27 (IBM, SPSS Tokyo, Japan), with the level of statistical significance set at $P < 0.05$. Unpaired t-tests compared the differences of demographic characteristics and the HIE manipulation between the IP and DP groups. Analyses of SIT scores from the pre- to post-session for each group were conducted using the paired t-test for each group. Each point of the kinematic and kinetic data was subjected to a two-way repeated-measures ANOVA to determine the effect of the HIE (pre- versus post-session), the condition (anticipated versus unanticipated) and any interaction effects.

Results

Demographic and acute high-intensity exercise manipulation analyses.

The mean and standard deviation for each participant's demographic characteristics and the physiological effects of the HIE excluding the warm-up period are displayed in Table 1. There were no significant differences between the groups in height, weight, any anatomical characteristics, HR variables, or RPE, except age and THR.

[Table 1 about here.]

Neurocognitive function.

SIT scores were not significantly different between the pre- and post-sessions. Comparing the pre- with the post-session, the participants were divided into an IP group (7 participants with increased scores) and a DP group (7 participants with decreased scores), respectively. The average score of the IP group significantly increased, while that of the DP group significantly decreased between the sessions (Table 2).

[Table 2 about here.]

Biomechanical analysis.

Interaction effect. Fig. 3 demonstrates the interaction effect on hip biomechanics during the side-step cutting tasks. In the IP group, the interaction effect of condition and time for peak hip abduction angle was significant. In the DP group, the interaction effect of condition and time for peak hip extension moment was significant.

Main effect for acute high-intensity exercise. Table 3 presents the main effects of the HIE on trunk and lower limb biomechanics, and ground reaction force during the side-step cutting tasks. In the IP group, the HIE led to decreased peak knee valgus moment (KVM), decreased peak GRF, increased angular displacement of pelvis rotation toward the dominant leg side, and increased knee flexion. In the DP group, the HIE resulted in increased angular displacement knee flexion.

[Table 3 about here.]

Main effect for anticipation. No significant effect for anticipation was observed for the main measurements.

Discussion

The effects of acute high-intensity exercise on neurocognitive function in athletes.

The results of the current study showed that neurocognitive performances improved in 7 participants (IP group) and decreased in 7 participants (DP group) after the HIE (Table 2). However, there were no significant differences between the groups in acute high-intensity exercise total time, HR, or RPE during the HIE (Table 1).

In the current study, we applied 80 % HRR, defined as high intensity according to the guidelines of the ACSM36) for the HIE. Wang et al.16) indicated that neurocognitive performances were significantly impaired in college-aged adults who conducted a bicycle ergometer exercise until reaching 80 % HRR and who then performed the Wisconsin Card Sorting Test as a neurocognitive test. While a general notion that HIE negatively affects neurocognitive performance has been proposed50), this theory does not always apply to trained individuals with high fitness levels and there is no consensus specifically for athletes28). As athletes are typically required to perform quickly and make critical decisions during exposure to high physical workloads23),24), they may be less cognitively affected by HIE than those with lower levels of fitness[28)]. Neurocognitive function may influence an athlete's decision-making and quick response in unanticipated athletic situations, resulting in performance level and injury risk[8)–11)]. Therefore, we set the HIE at an 80 % HRR intensity level[16),36)] to explore the effects of high-intensity load on neurocognitive function in athletes.

The results of the current study included athletes who had improved (IP group) and those who had decreased (DP group) neurocognitive function due to HIE (Table 2), suggesting that the effects of HIE on neurocognitive function may vary among individuals. Additionally, most of the HIE manipulation variables, such as the total HIE time, exercise HR, and RPE, which could affect neurocognitive function[19),50)], were not significantly different between the groups; however, age was significantly higher in the IP group compared to the DP group (Table 1). Therefore, there is a possibility that the IP group was more experienced in training and had a higher psychological stress tolerance for high-intensity physical loads[51)].

The SIT used as the neurocognitive test in this study reflects executive functions (i.e., high-order neurocognitive function)[40),41)]. Factors contributing to the improvement of executive function include exercise-induced prefrontal activation, as well as increased psychological arousal and pleasure levels[52)]. On the other hand, acute psychological stress is considered as one of the factors that impair executive function[53)]. Response to an acute stressor includes activation of the hypothalamus-pituitary-adrenal axis and subsequent release of adrenal hormones such as cortisol, noradrenergic or inflammatory activity[53)]. It has been suggested that the limited managerial resources of cognition are allocated to complex stress responses, thereby impairing executive function[54)]. Thus, the IP group may not have experienced significant psychological stress or biological processing when exposed to high-intensity physical loads. Consequently, the increase in exercise-induced neurocognitive performance among the IP group might have been facilitated by factors such as prefrontal activation, as well as increased psychological arousal and pleasure levels[52)].

In contrast, the DP group may have been vulnerable to the psychological stress of the HIE and consumed neurocognitive resources for biologic responses, leading to the impaired executive function[51)]. Additionally, multiple factors such as hypoxia, hypoglycemia, dehydration, and heat stress could have also led to the decreased neurocognitive performance[20),55)].

It would be difficult to explain changes in neurocognitive function with a single factor, as the neurocognition of healthy individuals results from the interaction of multiple processes and complex mechanisms[19)-21),52)-54)]. In the current study, direct measurements of physiological mechanisms such as neurotransmitters, hormones, and brain functions were not conducted, making it difficult to provide evidence to support the results. Additionally, the history of sports experience periods was not recorded. Future studies should employ a systematic approach to investigate the mechanisms underlying any changes in neurocognitive function. This would contribute to the development of training methods and conditioning techniques aimed at improving neurocognitive performance.

Effects of changes in neurocognitive function after acute high-intensity exercise on unanticipated motion.

The findings of the current study showed that peak KVM and peak GRF decreased in both conditions after the HIE in the IP group. An increase in KVM and GRF after ground contact have been established as biomechanical risk factors of ACL injuries by previous research56)–59). Therefore, the improvement of neurocognitive function after the HIE may have contributed to the reduction of ACL injury risk during the side-step cutting tasks.

The decrease in peak KVM after the HIE could have been related to the increase in angular displacement of pelvis rotation toward the dominant leg side. Villa et al.6) conducted systematic video analysis of ACL injuries and reported that the trunk rotated toward the uninjured limb in more than 50 % of the injuries. In the IP group, rotation of the pelvis toward the dominant leg side may have prevented knee abduction associated with hip internal rotation and contributed to the reduction in peak KVM. In addition, increasing the angular displacement of knee flexion may have reduced peak GRF by absorbing the impact from the ground.

SIT used in this study is widely known to reflect high-order neurocognitive functions[39]. High-order neurocognitive functions enable us to complete goal-oriented behavior and decision-making in complex situations[60]. Weiss et al.[61] suggested that higher neurocognitive function could reduce the reaction time from stimulus presentation to movement onset. Giesche et al.[22] revealed that high-level neurocognitive functions are related to task-related decision-making in unplanned landings. Therefore, the improvement of high-order neurocognitive function because of the HIE could have improved reaction time and decision-making, and as a result, led to stable motion.

On the other hand, the reason that the biomechanical risk factor of ACL injury did not change significantly in the DP group may be related to the persistence time of the effects of the HIE on neurocognitive function. A few studies have suggested that an improvement of neurocognitive function can be induced by short periods of exercise lasting as little as 10 minutes[19],[62], whereas a decrease of neurocognitive performance could be found after long period exercise lasting as long as 40 minutes[16],[17]. Additionally, previous studies have shown that neurocognitive performance is less affected by acute exercise after exercise than during exercise[63)]. Therefore, although the improvement of neurocognitive function in the IP group remained, the neurocognitive performance of the DP group could have returned to near-baseline levels after the HIE, and did not affect the dynamic trunk and knee movements.

In the results of the current study, the interaction effects of condition and time were observed in the peak hip abduction angle in the IP group and in the peak hip extension moment in the DP group, respectively. Hip joint control is more likely to play a vital role in preventing high-risk knee movements[6),64)]. Several investigations revealed an association between decreased hip abduction and increased knee valgus, possibly resulting in ACL injury[6),64)]. In the IP group, increased neurocognitive function after the HIE may have enabled individuals to make appropriate decisions in unanticipated conditions, resulting in an increased hip abduction angle. However, considering that KVM decreased in both conditions, it would be difficult to corroborate that the results were solely due to the hip joint. Greater external hip extension moments could result from increased activity in the rectus femoris muscle as an antagonistic force, leading to a higher amount of anterior tibial shear force and ACL loading[65)]. However, the DP group did not show an increase in knee extension moments; thus, the hip kinetics were less likely to affect the knee biomechanics. In the results of the current study, knee kinematics and kinetics that could occur as a result of biomechanical changes in the hip joint were not observed in either group. Knee biomechanics result from a complex human kinetic chain involving the trunk, hip, and ankle joints6),58),64). Furthermore, multiple risk factors such as neuromuscular and hormonal factors are simultaneously involved66). Thus, it is challenging to explain knee biomechanics solely through the planar motion of a single joint. Future research should take these multifactorial aspects into account and investigate their effects on knee biomechanics.

There were several limitations to the current study. First, the small sample size and inclusion of only collegiate athletes were among the limitations for broad generalization of these data. While the main effect of the HIE showed a large effect size67) (peak KVM: $\eta^2 = 0.18$, peak GRF: $\eta^2 = 0.55$), future research will need to recruit from a larger and more diverse sample size, encompassing various age groups. Second, multiple ACL injury risk factors such as neuromuscular and hormonal factors66) were not assessed in this study. Future studies should examine the combination of diverse risk factors, as it is challenging to identify a significant contribution to ACL injury from single planar biomechanics alone. Third, the motor tasks used in the laboratory setting could not completely mimic a realistic sports scenario. Replicating a more realistic sports environment will be required to better understand the potential relationship between neurocognitive function and ACL injury risk factors. Finally, we did not identify any factors associated with changes in neurocognitive function directly. Diverse contributing factors have been suggested to link to the changes in neurocognitive function during acute exercise[20)]. However, only SIT was used in this study. It would be difficult to consider all the factors because multiple factors are intricately involved in the changes in neurocognitive function through interactive processes. Suwabe et al.[68)] reported that evaluating oxygenated hemoglobin using fNIRS is an efficient measurement for identifying changes in cognitive function caused by acute exercise. Future research will be necessary using validated evaluations such as fNIRS.

Conclusion

The findings of this study showed that HIE caused some female athletes to have improved neurocognitive function and others to have decreased neurocognitive function. When grouped by improved and decreased neurocognitive function, respectively, the group with improved neurocognitive function showed a decrease in peak KVM and GRF during side-step cutting tasks in both anticipated and unanticipated conditions. Furthermore, the unanticipated condition post-HIE exercise showed different motion at the hip joint from the anticipated condition. These results suggest that the female athletes who improved neurocognitive function after HIE may reduce the biomechanical risk of ACL injury during side-step cutting tasks. Future research is required to increase the sample size and further evaluate factors related to changes in cognitive function.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Experiment conception and design: MK, SS and MT. Experiment implementation: MK. Data analysis: MK. Paper composition: MK. Analyzing and writing advisory: SS and MT. All authors approved the final version of the manuscript.

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Table 1. Participant characteristics and acute high-intensity exercise manipulation (mean ± SD).

Variables	**IP group (n = 7)**	**DP group (n = 7)**	***P* value**
Participants' Demographic Characteristics			
Age (year)	20.7 ± 1.6	19.0 ± 1.1	0.048*
Body height (cm)	161.3 ± 4.3	162.7 ± 5.2	0.616
Body weight (kg)	56.2 ± 3.9	57.7 ± 4.5	0.527
Q-angle (°)	3.0 ± 4.2	7.3 ± 2.8	0.059
Thigh-foot angle (°)	7.0 ± 5.9	8.7 ± 5.5	0.611
Leg-heel alignment (°)	3.1 ± 1.8	4.1 ± 1.5	0.313
Navicular drop test (mm)	3.4 ± 2.3	5.5 ± 4.3	0.315
Acute High-intensity Exercise Manipulation[a]			
Acute high-intensity exercise total time (s)	782.4 ± 162.8	736.7 ± 113.9	0.554
Resting HR (bpm)	57.0 ± 6.3	61.9 ± 3.9	0.110
THR (bpm)	165.3 ± 2.1	167.3 ± 1.0	0.043*
Exercise HR (bpm)	141.3 ± 7.2	147.1 ± 3.0	0.085
Mean RPE	14.1 ± 0.9	14.0 ± 1.9	0.926
Maximum RPE	17.3 ± 1.0	16.4 ± 1.7	0.271
Workload (kp)	1.8 ± 0.2	1.6 ± 0.1	0.079
Pedal speed (rpm)	84.2 ± 1.6	83.6 ± 1.4	0.415

IP: increased performance; DP: decreased performance; HR: heart rate; THR: target heart rate; RPE: rating of perceived exertion.

[a]Data are shown excluding the warm-up period.

*Significant difference between groups ($P < 0.05$).

Table 2. Pre-session and post-session Stroop Interference Test scores (Mean ± SD).

	Pre	**Post**	***P* value**
A total of participants (n = 14)	64.6 ± 12.6	65.1 ± 12.7	0.699
IP group (n = 7)	63.7 ± 9.7	68.6 ± 9.0	< 0.001*
DP group (n = 7)	65.6 ± 15.7	61.7 ± 15.5	< 0.001*

IP: increased performance; DP: decreased performance.

*Significant difference between groups ($P < 0.05$).

Table 3. The main effect of the acute exercise on trunk and lower limb biomechanics during the side-step cutting tasks (mean ± SD).

		Pre		**Post**		**F $_{(1, 32)}$**	**P**	**η^2**
		Anticipated	Unanticipated	Anticipated	Unanticipated			
Peak Kinetic Variables[a]								
Knee Var/Val Moment (Nm/kg)	IP group	− 0.1 ± 0.1	0.0 ± 0.2	0.0 ± 0.1	0.1 ± 0.2	9.08	0.024*	0.18
	DP group	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.1	0.1 ± 0.1	0.11	0.752	0.02
GRF (%BW)	IP group	3.3 ± 2.1	3.8 ± 2.1	3.1 ± 3.4	3.6 ± 3.6	7.37	0.035*	0.55
	DP group	3.8 ± 4.9	4.0 ± 5.3	3.7 ± 5.1	3.7 ± 3.9	4.81	0.071	0.45
Angular displacement[b]								
Pelvis rotation toward the dominant leg side (°)	IP group	4.4 ± 1.6	3.9 ± 2.0	5.5 ± 2.7	6.3 ± 2.5	7.39	0.035*	0.55
	DP group	4.1 ± 1.7	7.5 ± 4.5	5.0 ± 3.8	7.1 ± 1.7	0.14	0.719	0.02
Knee Flx/Ext (°)	IP group	45.2 ± 3.2	45.0 ± 2.5	46.3 ± 5.0	50.6 ± 2.0	14.58	< 0.001*	0.71
	DP group	45.6 ± 2.8	42.7 ± 4.9	45.8 ± 5.1	49.1 ± 4.4	10.75	0.017*	0.64

IP: increased performance; DP: decreased performance.

[a] Peak Variables. Var/Val, varus (+)/valgus (–); GRF, ground reaction force.

[b] The difference between the maximum and minimum joint angles. Flx/Ext, flexion (+)/extension (–).

* Significant main effect of the acute exercise ($P < 0.05$).

Fig. 1. Experimental procedures.

[a] Immediately after reaching the target heart rate, the participants were asked to perform the Stroop Interference Test and to maintain the pedal speed until the end of the test.

Fig. 2. The procedure of experimental tasks.

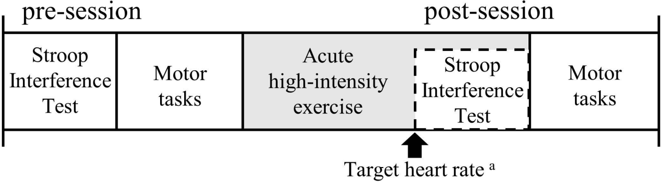
(1) Participant stood while stepping on the footswitch with their dominant leg on a 30cm high box.

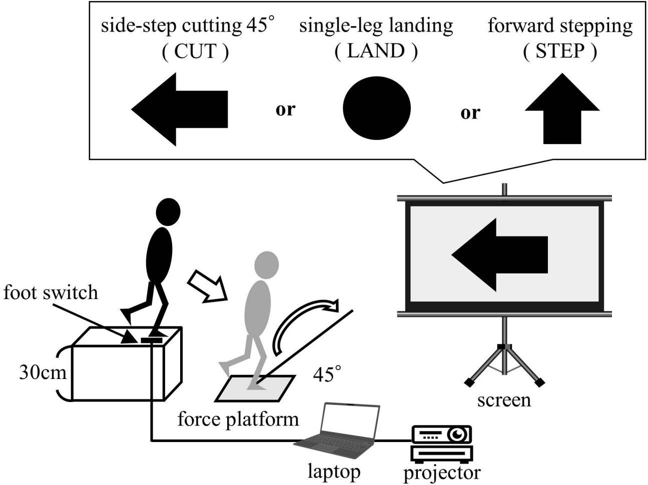
(2) Immediately after the participant jumped off the box, the experimental task was displayed on the screen.

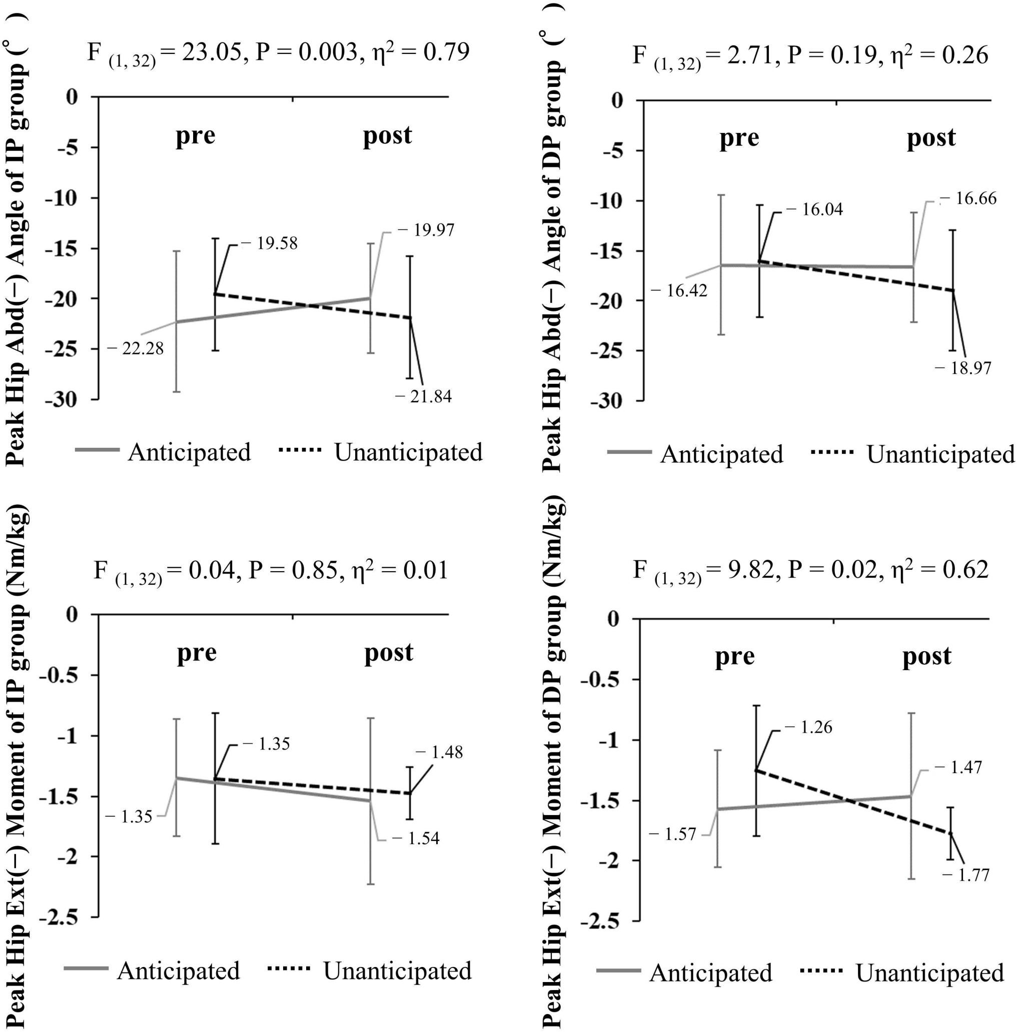
(3) Participant reacted to the instruction displayed on the screen.

Fig. 3. Interaction effect on hip biomechanics during the side-step cutting tasks (mean±SD).[a]

[a] Peak variables. Flx/Ext, flexion(+)/extension(–); Add/Abd, adduction(+)/abduction(–)


pre-session
post-session
Stroop Interference Test
Motor tasks
Acute high-intensity exercise
Stroop Interference Test
Motor tasks
Target heart rate a


side-step cutting 45°
(CUT)
single-leg landing
(LAND)
forward stepping
(STEP)
or
or
foot switch
30cm
45°
force platform
screen
laptop
projector


Peak Hip Abd(−) Angle of IP group (°)
F (1, 32) = 23.05, P = 0.003, η2 = 0.79
0
-5
-10
-15
-20
-25
-30
pre
post
− 19.58
− 19.97
− 22.28
− 21.84
Anticipated
Unanticipated
Peak Hip Abd(−) Angle of DP group (°)
F (1, 32) = 2.71, P = 0.19, η2 = 0.26
0
-5
-10
-15
-20
-25
-30
pre
post
− 16.04
− 16.66
− 16.42
− 18.97
Anticipated
Unanticipated
Peak Hip Ext(−) Moment of IP group (Nm/kg)
F (1, 32) = 0.04, P = 0.85, η2 = 0.01
0
-0.5
-1
-1.5
-2
-2.5
pre
post
− 1.35
− 1.48
− 1.35
− 1.54
Anticipated
Unanticipated
Peak Hip Ext(−) Moment of DP group (Nm/kg)
F (1, 32) = 9.82, P = 0.02, η2 = 0.62
0
-0.5
-1
-1.5
-2
-2.5
pre
post
− 1.26
− 1.47
− 1.57
− 1.77
Anticipated
Unanticipated