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ORIGINAL

Reactive Neuromuscular Training and Dynamic Lower Extremity Postural Control: A Single-Blind Randomized Control Trial

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Objective: Neuromuscular training may often result in an incomplete improvement of biomechanical risk factors associated with non-contact ACL injury. This study aimed to investigate the effects of reactive neuromuscular training (RNT) on dynamic postural control of the lower extremity during single-leg drop landing (SLDL) in comparison with conventional neuromuscular training (CNT).

Method: Twenty-eight recreational female athletes were randomized to a CNT group (n=15) or a RNT group (n=13). All participants performed SLDL for three-dimensional motion analysis before and after CNT and RNT. The kinematic variable was calculated from before 50 milliseconds (ms) to after 100 ms initial contact: joint angle (degree). The kinetic variable was calculated from initial contact to after 100 ms: internal net joint moment (Nm/kg). Time series curve for normalized data was represented for group means and associated 95% confidence intervals. Effect sizes using Cohen's *d* was also calculated.

Results: In within-group differences, the CNT group showed decreased knee flexion angle (0~100% of the task) and decreased knee valgus angle (0~50% of the task) after the intervention, whereas the RNT group showed increased hip flexion angle (0~14% of the task), decreased hip adduction angle (0~100% of the task), and decreased knee valgus angle (0~100% of the task) after the intervention. In between-group differences, the RNT group exhibited more hip flexion angle (0~49, 61~91% of the task), more knee flexion angle (0~100% of the task), and less knee valgus angle (0~55% of the task) than the CNT group.

Conclusion: These findings suggest that both training intervention programs modified dynamic posture of the hip and knee during SLDL. Therefore, combining a neuromuscular training program with RNT technique would be more efficient for future injury prevention efforts.

Keywords: Neuromuscular training, Reactive neuromuscular training, Anterior cruciate ligament injury, Dynamic postural control, Biomechanics

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INTRODUCTION

Anterior cruciate ligament (ACL) injury may result in long-term disability such as post-traumatic osteoarthritis and can have associated socio-economic problems (Montalvo et al., 2019; Sugimoto, Myer, Foss & Hewett, 2015). In terms of gender differences, studies have consistently shown that female athletes have a higher non-contact ACL injury rate than males in sports (Arendt & Dick, 1995; DeHaven & Lintner, 1986). Especially, during sport-related movements that require jump-landing and/or sudden changes in direction, the females are up to six times more likely to suffer a non-contact ACL injury compared with males (Arendt, Agel & Dick, 1999; Harmon & Ireland, 2000). These results are because women have biomechanical and neuromuscular characteristics that different from men in the lower extremity when performing common athletic tasks (Henry & Kaeding, 2001; Lephart, Ferris, Riemann, Myers & Fu, 2002). Thus, the main issue for preventing non-contact ACL injury in female athletes is to address these neuromuscular and biomechanical characteristics.

Abnormal neuromuscular control during dynamic activities can lead to altered lower extremity biomechanics including hip adduction and internal rotation, knee flexion, abduction and external rotation (Hewett, Myer & Ford, 2006; Mehl et al., 2018). This neuromuscular control deficits result in poor postural control during jump-landing tasks and, it may be one determinant of the ACL injury mechanism in female athletes (Hewett, Ford, Hoogenboom & Myer, 2010; Hewett et al., 2005; Lopes et al., 2018; Malinzak, Colby, Kirkendall, Yu & Garrett, 2001). Thus, the ability to execute the proper dynamic posture of the hip and knee joint during landing is crucial to reducing the risk of injury, and this ability needs to be honed in ACL injury prevention programs (Nessler, Denney & Sampley, 2017).

Neuromuscular training which improves neuromuscular control of the lower extremity biomechanics during a landing task may be required to adapt the motor program for the maintenance and accomplishment of postural control (Brown, Palmieri-Smith & McLean, 2014; Horak, Nashner & Diener, 1990; Myer, Ford, Brent & Hewett, 2006; Pfile et al., 2013; Riemann & Lephart, 2002). However, some studies reported that the biomechanical variables associated with non-contact ACL injury are not as sensitive to neuromuscular-based training (Brown et al., 2014; Chappell & Limpisvasti, 2008; Greska, Nelson Cortes, Van Lunen & Oñate, 2012; Lephart et al., 2005; Lopes et al., 2018; Myer, Ford, McLean & Hewett, 2006; Pappas et al., 2015). The reason for the conflicting findings could be a lack of consideration during conventional neuromuscular training (CNT) for stimulating appropriate stabilizing reactions allowing for the control of high-risk joint translation during landing tasks. Furthermore, no studies have described the types of neuromuscular training conducted to improve neuromuscular control in lower extremity biomechanics during landing.

The concept of reactive neuromuscular training (RNT), first introduced by Voight and Cook, is to train individuals to recognize good movement by themselves through an external force (Cook, Burton & Fields, 1999; Voight & Cook, 1996). In other words, this training approach aims to restore altered neuromuscular control systems by giving athletes information on high-risk movements in advance (Hoogenboom, Voight & Prentice, 2014; Lephart, Pincivero, Giraido & Fu, 1997). Some studies support the use of RNT in muscular imbalance (Cook et al., 1999), balance ability (Kim, 2012) and knee abduction moments (Pittman, 2013). Nevertheless, evidence is limited on improvements in dynamic posture and prevention of non-contact ACL injury brought about by RNT. Therefore, the effectiveness of RNT on dynamic postural control should be investigated.

Thus, our study aimed to determine the extent to which RNT could successfully modify the three-dimensional biomechanics of the hip and knee joints following single-leg drop landing (SLDL) in female athletes and compared the findings with those of CNT. We hypothesized that there are differences between RNT and CNT in their effects on the kinetic and kinematic patterns of the hip and knee joints during SLDL.

METHODS

1. Study design

We followed a randomized controlled trial design with intervention blinding. The independent variables were group (RNT and CNT) and time (preintervention, postintervention), and the dependent variables were three-dimensional kinematics (joint angle) and kinetics (net internal joint moment) of the hip and knee during SLDL. Study approval was obtained from the Institutional Review Board of Yonsei University and written informed consent was obtained from all participants before participation (7001988-202003-HR-812-02).

2. Participants

We recruited 32 healthy female recreational athletes from the university and the surrounding community. A recreational athlete was defined as an individual who engages in sports or exercise involving unilateral landing tasks (e.g., soccer, basketball, volleyball, and so on) one to three times per week or who previously participated in such sports at the varsity level in high school and competed at least once a month. All participants were randomized to a CNT group (n=15) or an RNT group (n=15). We excluded a participant if she (1) did not meet the criterion for an age of between 20 and 30 years old, (2) did not meet the recreational athlete criterion, (3) had a surgery or injury in the lower extremity within 6 months before the study, (4) had cardiovascular, respiratory, neurological, or other disease that prevented her from engaging in submaximal effort in sports activity, (5) had ever suffered an ACL injury, or (6) had participated in a formal injury prevention training within 6 months before the study. Throughout the study, participants could continue their aerobic or sports activities before they participated in this study but could not initiate new aerobic.

3. Procedure

The procedures are outlined in Figure 1. After enrollment, three-dimensional joint angles and moments of the hip and knee were measured using an eight-camera motion analysis system (Vicon Motion Systems, Oxford Metric Ltd., UK) at a sampling rate of 200 Hz. Ground reaction force data were also collected using an embedded force platform (AMTI, Watertown, MA, USA) with a sampling rate of 2,000 Hz. We time-synchronized the force plates to the motion analysis system to determine initial contact during SLDL.

We attached 16 retroreflective markers (11 mm) to landmarks of the lower extremities (bilaterally: anterior superior iliac spine, posterior superior iliac spine, lateral thigh, lateral knee, lateral tibia, lateral malleolus, second metatarsal head, and calcaneus). We initiated motion analysis by asking the participants to stand in a neutral position (the anatomical position) for 5 s, which was captured by placing their feet on the two force plates to set the standard angle. Then, they performed an SLDL on their dominant leg, which is defined as their preferred kicking leg (Brophy, Silvers, Gonzales & Mandelbaum, 2010) (Figure 2). Next, the participants were asked to stand with their non-dominant leg on a 30 cm-high platform and to drop from the platform and land onto the middle of a force plate using the dominant leg (Teng, Kong & Leong, 2017). An assistant researcher demonstrated the testing sequence. We allowed the participants to go through several practice trials so they could correctly execute the required movements. During the test, the tasks were repeated until data from three successful trials were achieved. A trial was successful

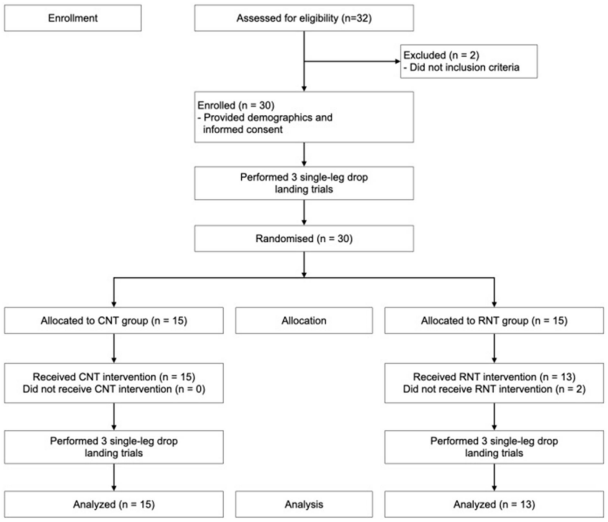

Figure 1. Consolidated Standards of Reporting Trials (CONSORT) flow diagram. CNT: Conventional Neuromuscular Training, RNT: Reactive Neuromuscular Training

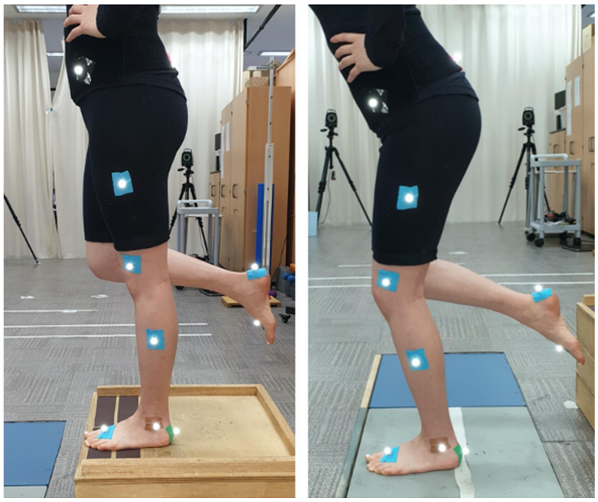

Figure 2. Preparation for SLDL task (left: preparation for SLDL task, right: stable landing posture)

when the participant stepped off the platform without any jump action and adopted a stable landing posture without losing balance. After 6-week training intervention, all participants completed a postintervention assessment.

4. Training intervention

The participants were divided into two groups. One group underwent a CNT program that was based on previously published studies on improvements of potential biomechanical risk factors of ACL injury (Hopper, Haff, Joyce, Lloyd & Haff, 2017; Lopes et al., 2018) (Table 1). The second group underwent a RNT program that was a modification of the CNT program and included the RNT technique, which involves educating the participants regarding lower extremity valgus motion through external resistance with an elastic band (Table 2). During the session, they should exert every effort to maintain and return to the neutral position of the lower extremity by resisting the valgus force applied by an instructor. The instructor gave verbal guidance like "resist the force I'm applying" or "try to keep your posture" so that the participants could perform the movement correctly. The instructor controlled the resistance level so as not to apply excessive feedback to the participants, cause functional failure, or cause the participants pain or discomfort during the training. For both training groups, the training intervention lasted 6 weeks and consisted of three sessions per week of not more than 20 min each, as described previously (Hewett et al., 2006; Pappas et al., 2015; Sadoghi, von Keudell & Vavken, 2012). The sessions were conducted on non-consecutive days, for a total of 18 training sessions. Both groups were instructed to perform a dynamic warm-up before each session.

Table 1. Conventional neuromuscular training program

Exercise	Set	Time or repetition	Rest
Phase 1 (for weeks 1 through 2)			
Double leg squat and push off	2	12 reps	60
Double leg squat jump	1	8 reps	
Double leg jumps and stick	2	6 reps	
Forward barrier jump	2	15 sec	
Broad jump (forward, vertical)	1	8 reps	
Phase 2 (for weeks 3 through 4)			
Double-leg squat jump	1	8 reps	60
Single leg push-off	1	6 reps	
Single leg squat	1	6 reps	
Crossover hop and stick (right to left)	2	6 reps	
Single leg hops and stick	2	6 reps	
Forward barrier hops	2	15 sec	
Phase 3 (for weeks 5 through 6)			
Double-leg squat jump	1	6 reps	60
Single leg squat jump	1	4 reps	
Broad jump (forward, vertical)	2	6 reps	
Broad hops (forward, vertical)	2	5 reps	
Single leg hops and stick	2	5 reps	
Crossover hop and stick (right to left)	2	6 reps	

5. Data processing and statistical analysis

Each participant's joint angles and net internal joint moments of the hip and knee were computed and analyzed in the sagittal, frontal, and transverse planes during preintervention and postintervention SLDL. Non-contact ACL injuries likely occur in the first 100 milliseconds (ms) after initial ground contact (Dai et al., 2018; Koga et al., 2010). Therefore, joint angles (degree) were analyzed over a 150 ms time interval from 50 ms before initial contact to 100 ms after initial contact. Net internal joint moments (Nm/kg) were also analyzed over a 100 ms time interval from initial contact to 100 ms after IC. Initial contact was defined as the point where the force plate data reached more than 10 N. The time intervals were reduced to 100 frames so that each frame represented 1% of the task. All outcome measures were analyzed as an average of three trials.

We used RStudio (RStudio Inc, US) to plot the time series curve for normalized kinematic and kinetic data across 100% of the SLDL. Group means and associated 95% confidence intervals (CIs) were represented for the entire task. Areas where the CIs for at least 3 consecutive percentage points did not overlap between the curve were considered differences. We calculated the mean differences and associated standard deviations for the identified increments (Weltman, 2013). Addition-

Table 2. Reactive neuromuscular training program

Exercise	Set	Time or repetition	Rest
Phase 1 (for weeks 1 through 2)			
Double leg squat and push off (with RNT technique)	2	12 reps	60
Double leg squat jump (with RNT technique)	1	8 reps	
Double leg jumps and stick (with RNT technique)	2	6 reps	
Forward barrier jump	2	15 sec	
Broad jump (forward, vertical) (with RNT technique)	1	8 reps	
Phase 2 (for weeks 3 through 4)			
Double-leg squat jump (with RNT technique)	1	8 reps	60
Single leg push-off (with RNT technique)	1	6 reps	
Single leg squat (with RNT technique)	1	6 reps	
Crossover hop and stick (right to left) (with RNT technique)	2	6 reps	
Single leg hops and stick (with RNT technique)	2	6 reps	
Forward barrier hops	2	15 sec	
Phase 3 (for weeks 5 through 6)			
Double-leg squat jump (with RNT technique)	1	6 reps	60
Single leg squat jump (with RNT technique)	1	4 reps	
Broad jump (forward, vertical) (with RNT technique)	2	6 reps	
Broad hops (forward, vertical) (with RNT technique)	2	5 reps	
Single leg hops and stick (with RNT technique)	2	5 reps	
Crossover hop and stick (right to left) (with RNT technique)	2	6 reps	

ally, we calculated Cohen's *d* effect sizes for all dependent variables using mean differences and associated pooled standard deviations to interpret within- and between-group differences after the intervention (Slater & Hart, 2016). Effect sizes will be interpreted as small (< 0.40), moderate (0.40~0.80), or large (> 0.80) (Cohen, 1992). Independent-sample *t*-test was used to assess group differences in primary demographics.

RESULTS

There were no statistically significant differences between CNT and RNT groups in demography characteristics: age (CNT: 23.7±2.9 yr., RNT: 25.9±2.8 yr., p = .059), height (CNT: 166.7±6.5 cm, RNT: 162.4±5.0 cm, p = .063), and body mass (CNT: 61.2±7.5 kg, RNT: 56.1±9.1 kg, p = .114). RNT group of this study was analyzed only 13 except 2 participants who discontinued intervention.

1. Within-group difference

At postintervention, both groups demonstrated significant within-group improvement in kinematics. In the CNT group, the knee flexion angle decreased at 0~100% of the task (mean difference = 7.05°; Cohen *d* range = -1.27 to -0.88; Figure 3A). In addition, the knee valgus angle decreased at 0~50% of the task (mean difference = 4.92°; Cohen *d* range = 0.99 to 1.43; Figure 3A). In the RNT group, the hip flexion angle increased at 0~14% of the task (mean difference = 6.21°; Cohen *d* range = 0.87 to 0.94; Figure 4A). The hip adduction angle decreased at 0~100% of the task (mean difference = 9.19°; Cohen *d* range = -2.67 to -2.07; Figure 4A). Similarly, the knee valgus angle decreased at 0~100% of the task (mean

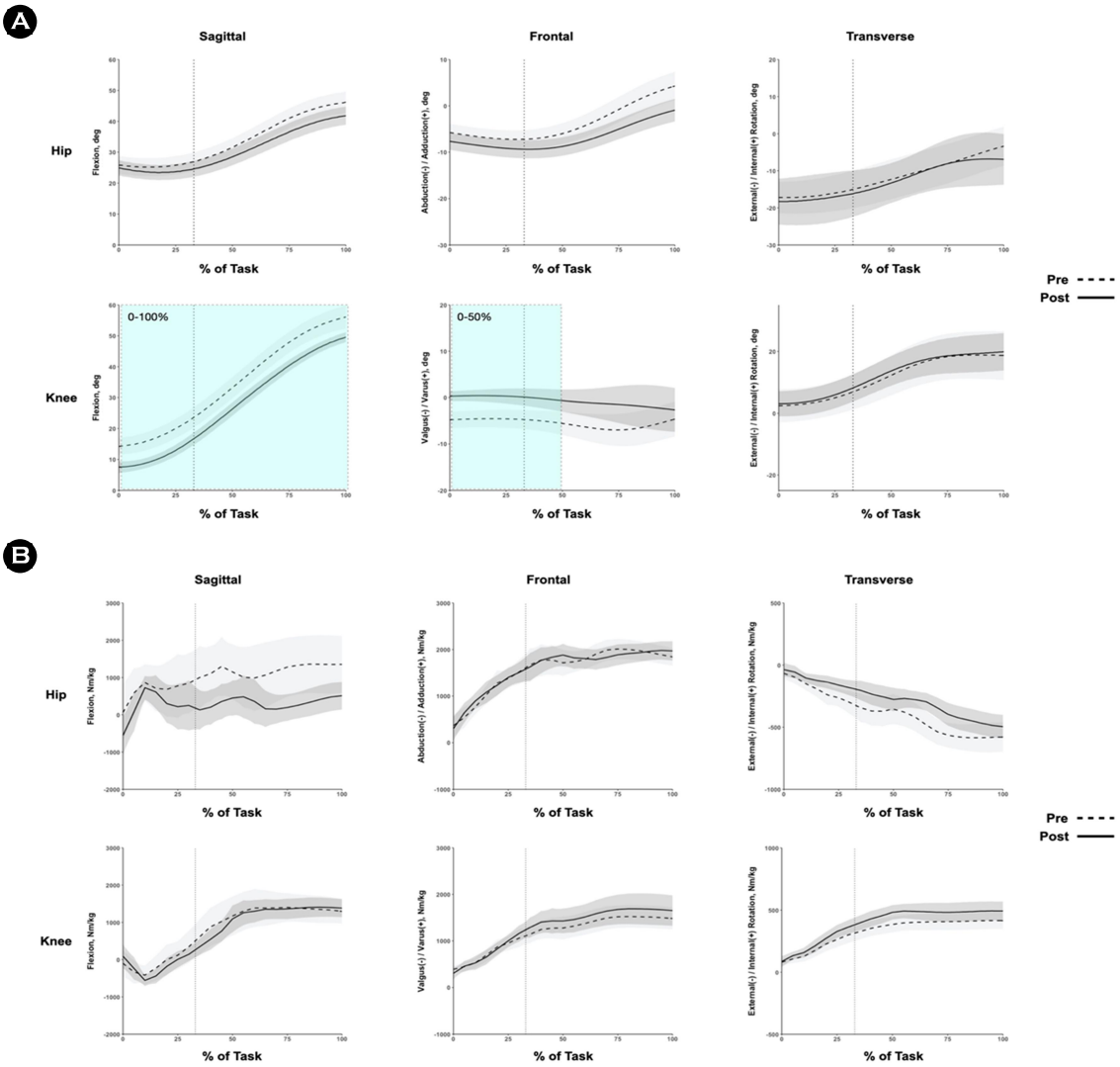

Figure 3. Pre- and postintervention kinematics and kinetics in the CNT group. The group means ± 95% confidence intervals throughout the entire task are indicated. The vertical dotted line indicates initial contact. Blue bands indicate significant differences between pre- and postintervention. A, kinematics. B, kinetics.

difference = 11.75°; Cohen *d* range = 1.69 to 2.61; Figure 4A). The differences in all kinetic outcomes were not significant (Figure 3B and 4B).

2. Between-group difference

The RNT group exhibited more hip flexion angle at 0~49% (mean difference = 5.94°; Cohen *d* range = -1.61 to -1.07) and 61~91% (mean difference = 5.68°; Cohen *d* range = -1.26 to -1.09) of the task, respectively (Figure 5A), compared with the CNT group. Similarly, compared with the CNT group, the RNT group showed more knee flexion angle at 0~100% of the task (mean difference = 7.1°; Cohen *d* range = -2.28 to -1.06) and less knee valgus angle at 0~55% (mean difference = 5°; Cohen *d* range = -1.55 to -0.95; Figure 5A). We found no significant differences in all kinetic outcomes (Figure 5B).

DISCUSSION

Essentially, both training programs in our study focused on the correction of movement patterns that may increase injury risk during SLDL. After the intervention, both groups exhibited

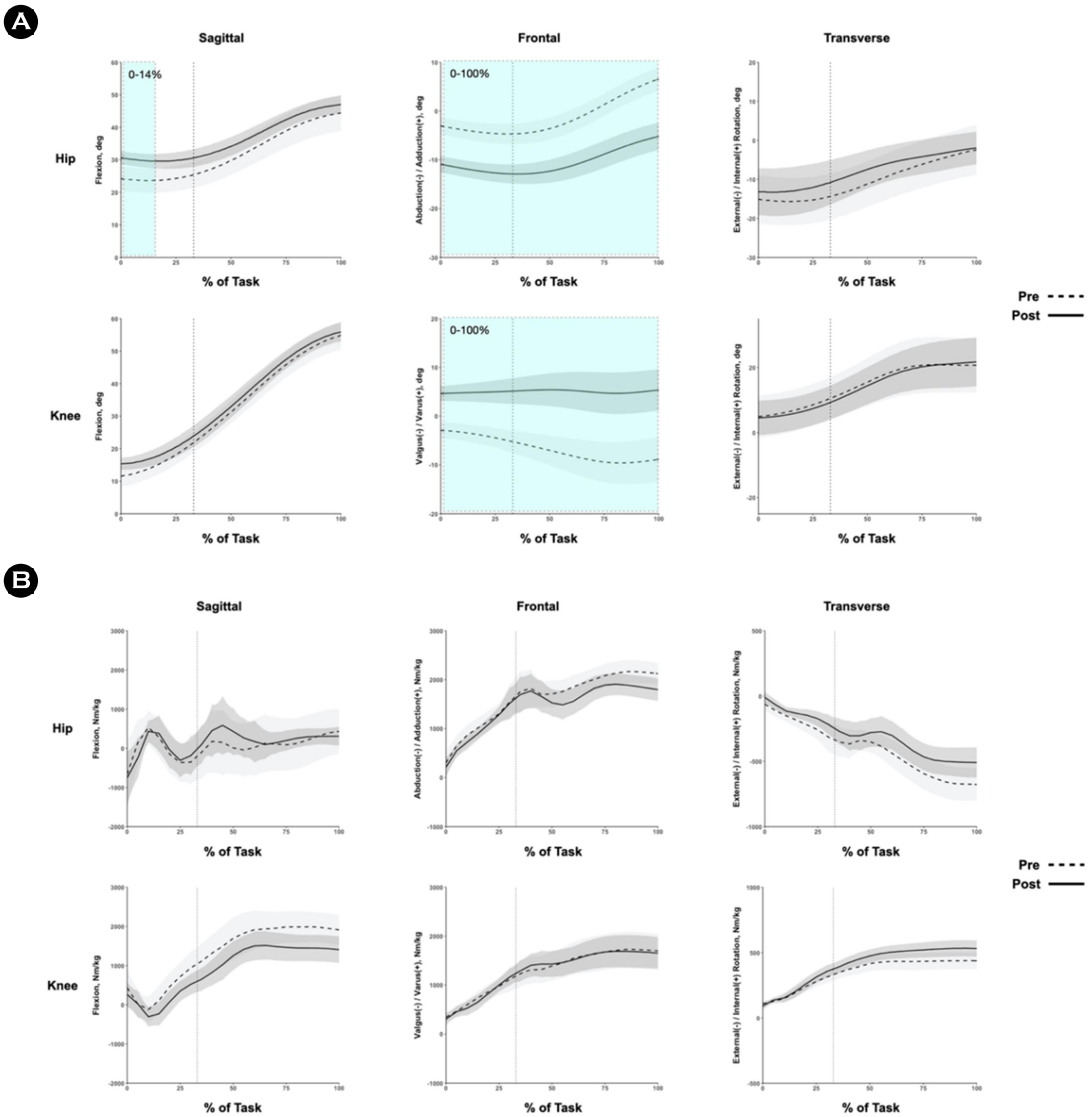

Figure 4. Pre- and postintervention kinematics and kinetics in the RNT group. The group means ± 95% confidence intervals throughout the entire task are indicated. The vertical dotted line indicates initial contact. Blue bands indicate significant differences between pre- and postintervention. A, kinematics. B, kinetics.

less knee valgus angle than before the intervention. Specifically, the RNT group showed a much smaller knee valgus angle than before the intervention during the entire landing task. Although significant differences in the CNT group were observed mainly before initial contact, this finding is similar to those of other studies on the effect of neuromuscular training on biomechanics in the lower extremity (Hopper et al., 2017; Myer, Ford, McLean, et al., 2006).

A significant decrease in hip adduction and knee valgus angle was observed in the RNT group from the beginning of the pre-landing phase (before initial contact) to after initial contact. This may be attributed to the RNT technique, which enabled the RNT group to maintain the hip-abducted and knee-adducted posture throughout the training sessions. Due to this external force applied to their knee, the RNT group seems to have utilized their feed-forward motor control system to perform reduced adduction angles of the hip from the pre-landing phase. On the other hand, we found no significant change in the frontal plane motion of the hip within the CNT group. We presume that the participants in the CNT group

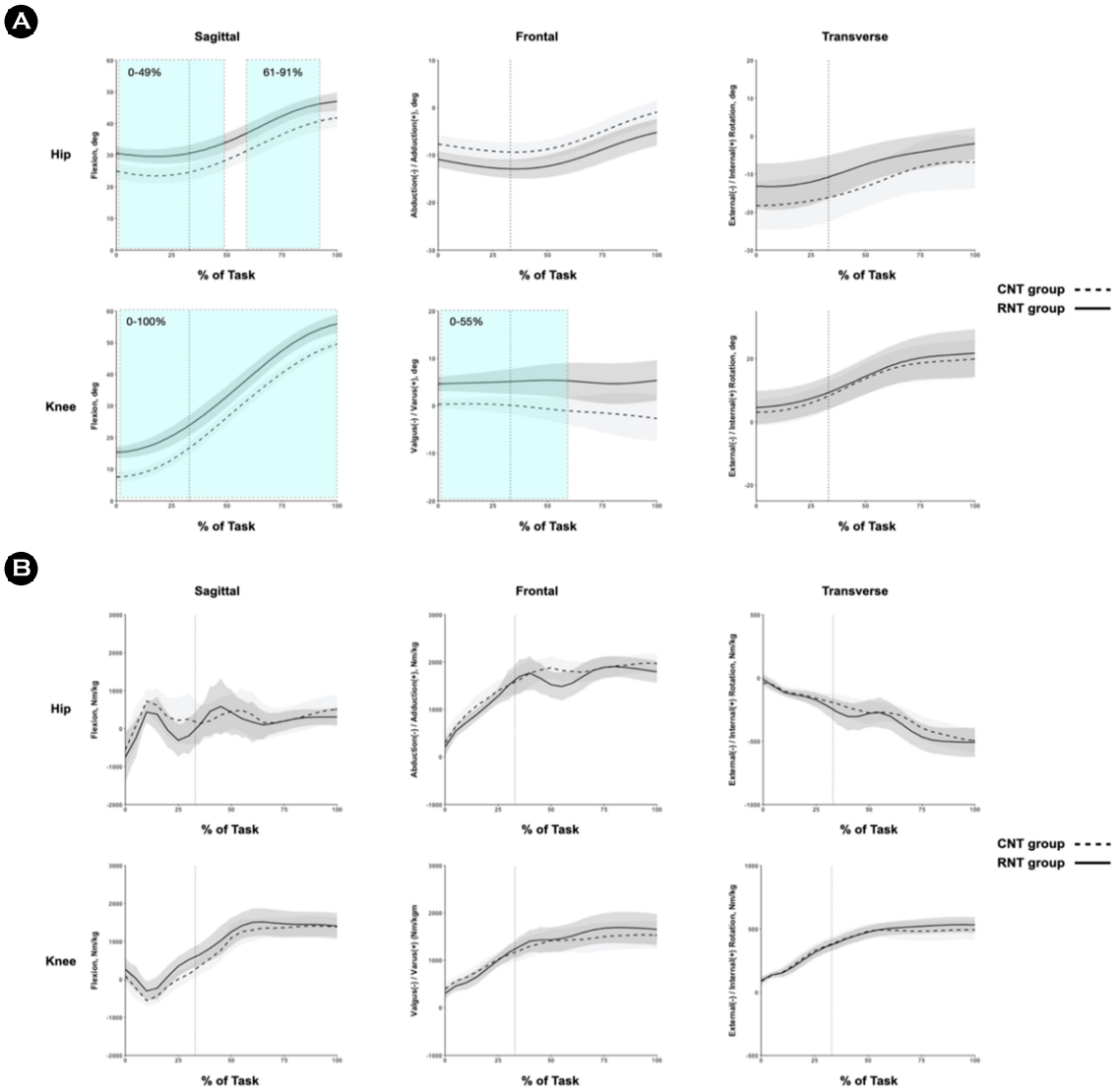

Figure 5. Postintervention kinematics and kinetics between the groups. The group means ± 95% confidence intervals throughout the entire task are indicated. The vertical dotted line indicates initial contact. Blue bands indicate significant differences between the groups. A, kinematics. B, kinetics.

performed the movement primarily by using the knee control strategy. In fact, we found that the CNT group showed only decreased knee valgus motion after the training intervention program they experienced. This perspective corroborates with the findings of a previous study suggesting that valgus collapse of the lower extremity during single leg tasks is governed primarily by knee motion rather than by the hip and ankle (Myer, Ford, McLean, et al., 2006). However, although the RNT group showed a significant change in both the hip and knee motion, this does not necessarily indicate that the CNT program is inferior to the RNT program in improving postural control ability. There is a possibility that the largely decreased hip adduction angle in the RNT group may be due to lateral pelvic drop or trunk lean towards the stance leg. This ipsilateral pelvic drop or trunk lean can cause a shift in center of mass towards the stance leg, increasing hip abduction motion (Chijimatsu et al., 2020). Unfortunately, due to the limitations of measuring instruments, we were unable to investigate pelvic and trunk kinematics. Future research investigating the effects of RNT on pelvic and trunk in compared to CNT is required.

The participants in the CNT group showed a decreased knee flexion angle after the intervention throughout the entire phase from pre-landing to post-initial contact. Although this finding is in direct contrast to those of previous studies (Brown et al., 2014; Chappell & Limpisvasti, 2008; Lephart et al., 2005), we hypothesize that this would be due to postural adaptation to single leg-focused training. Typically, discrepancies may occur in sagittal plane motion due to the distinct biomechanical demands of each type of landing task (Brown et al., 2014). For instance, unilateral landing is characterized by a decrease in knee flexion at touchdown (Weinhandl, Joshi & O'Connor, 2010). This motion may be a compensatory strategy for decelerating the body efficiently and absorbing the impact forces of landing by reducing the moment arm of the body center of mass in the sagittal plane (Pappas, Hagins, Sheikhzadeh, Nordin & Rose, 2007). The CNT program used in our study mainly consisted of exercise elements related to single leg movement. In addition, the participants performed the CNT program with no verbal instruction regarding soft landing techniques which can lead to a deep knee flexion motion. Further research is needed to confirm our evaluations.

At postintervention, the RNT group performed SLDL with less knee abduction angle than the CNT group during the entire pre-landing and early stance phases of the task. This finding can be interpreted in two contexts. The first interpretation is that the RNT technique elicited a reactive movement through reflex pathways, thus the RNT group were able to control their knee valgus posture in the frontal plane better than the CNT group. This premise agrees with the findings of a previous study (Dhaher, Tsoumanis & Rymer, 2003). This reflex response may be important in preserving knee joint stability by activating regional muscles and inducing widespread muscle activation throughout the lower extremity. In this context, the RNT program may have induced reflex activity in the knee muscles, thereby facilitating the ability to prepare for an anti-valgus posture from the pre-landing phase. Further electromyographic studies are needed. The second interpretation is that the RNT group showed 'excessively' adducted knee posture due to the RNT technique while the CNT group showed a frontal plane neutral posture of the knee at postintervention. We speculated that a valgus force through the RNT technique with a resistance band caused externally rotated foot position at landing. In fact, foot rotation positions can influence knee valgus/varus motion during unilateral landing task (Teng et al., 2017). However, only the hip and knee joints were examined in our study, which should be addressed in future studies.

The RNT group further showed a greater hip and knee flexion motion compared with the CNT group during SLDL, specifically showing a significant increase in the knee flexion motion after the 6 week-training intervention. This may indicate that the RNT participants had relatively softer landings than the CNT group. Increased sagittal plane motion during the landing task may reduce strain on the ACL (Beynnon et al., 1995; Hirokawa, Solomonow, Lu, Lou & D'Ambrosia, 1992). In this context, the RNT may be relatively better than the CNT in improving neuromuscular control in sagittal plane motion and in reducing non-contact ACL injury risk during single-leg landing. However, in terms of within-group differences, the RNT group showed no significant change in knee flexion and no other significant differences in kinetics. Thus, future research is required to describe further the effects of RNT on dynamic hip and knee postures in the sagittal plane.

Our study has several limitations. First, only one type of landing task was examined. Most other studies that investigated the effects of neuromuscular training on landing biomechanics evaluated a variety of landing-related tasks. This is a significant limitation of this study since non-contact ACL injury occurs during several athletic movements in sports. Therefore, understanding the effects of reactive neuromuscular training program on movement biomechanics during these types of tasks is important. Second, the RNT program in this study only involved knee valgus perturbation for about 20 min. Future studies are needed to identify the effects of hip joint perturbation and training durations of less than 20 min to get the maximal effect with minimal effort for non-contact ACL injury prevention.

CONCLUSION

Both the 6-week CNT and RNT programs for recreational female athletes resulted in postural control change in the hip and knee during single-leg drop landing. In particular, the RNT program was more efficient over the same amount of time. The potential risk of non-contact ACL injury can be decreased in recreational female athletes by adopting an injury prevention strategy that combines a neuromuscular training program with the RNT technique.

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