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Effects of Hip Adduction and Abduction Forward Lunge on Muscle Activity and Center of Pressure in Healthy Subjects: A Pilot Study

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Abstract: Patellofemoral pain syndrome (PFPS) ranks among the most prevalent factors causing anterior knee pain. Quadriceps exercises such as forward lunges are important to treat PFPS. Aim: We investigated whether there is a difference in muscle activity between the vastus medialis oblique (VMO) and vastus lateralis (VL) muscles and the center of pressure (CoP) among three hip positions, namely, hip adduction forward lunge (HADF), hip neutral forward lunge (HNEF), and hip abduction forward lunge (HABF), in healthy subjects. Method: This was a randomized controlled pilot study that included twenty healthy (age: 23.7 ± 2.51) volunteers. The CoP was measured using a "Wii Balance Board" from Nintendo, and VMO and VL muscle activity were measured via wireless surface electromyography. Results: The CoP outcomes showed significant differences among the three positions in terms of position ($p < 0.001$), sum distance ($p < 0.001$), range ($p < 0.001$), and max distance ($p < 0.001$). VMO ($p < 0.000$), and VL ($p < 0.005$) muscle activity and the ratio of VMO/VL ($p < 0.000$) significantly differed among the three positions. Conclusions: Although VMO and VL muscle activity increased in the HADF and HABF, excessive changes in the CoP occurred in the two positions. The change in the CoP during the HADF and HABF may result in valgus, varus, and loading of the knee joint, which may worsen PFPS. The HNEF is recommended for quadriceps strengthening in healthy subjects and PFPS patients.

Keywords: abduction; adduction; center of pressure; muscle activity; patellofemoral pain syndrome

1. Introduction

Patellofemoral pain syndrome (PFPS) represents a frequent knee joint disorder seen in clinical settings. Collins et al. suggest expanding research into patellofemoral pain syndrome as a means of reducing the impact of knee injuries [1]. PFPS is a prevalent type of knee pain affecting both adults and young individuals, including those who lead an active and healthy lifestyle [2]. Pain caused by PFPS is often worsened by prolonged sitting or climbing stairs. This has a significant impact on a person's daily activities [3]. A meta-analysis showed that squatting was the most sensitive physical examination assessment for PFPS [4]. The cause of PFPS is unknown, but it is most likely the outcome of a number of different factors, including training techniques. According to research, four significant factors contribute to the condition: imbalances in the lower extremity or patella, muscle imbalances in the lower extremity, overuse, and traumatic events [5]. Of these four factors, overuse is the cause in the vast majority of cases [6].

A systematic review found that lower quadriceps strength is associated with a significantly higher proportion of patellar instability-related knee pain [7]. There is compelling evidence that muscle imbalances play a pivotal role in the development of PFPS [3]. Many

previous studies have focused on the dysfunction of the vastus medialis oblique (VMO) and vastus lateralis (VL) muscles in PFPS patients, as these muscles attach directly to the patella [8,9]. Such studies have shown that an asymmetry in the activation of the VMO and VL muscles is associated with lateral patellar tracking in patients with PFPS [8,9].

Knee valgus is another mechanism associated with PFPS. With knee valgus, a knee will collapse medially due to pronounced supination, internal rotation, external rotation, or all of these factors [10]. The outward force on the patella increases and leads to hallux valgus. Female athletes are at a greater risk of presenting with dynamic valgus, potentially elucidating the higher rate of PFPS incidences in women [11]. Several studies indicate that valgus deformity of the knee is not due to the knee joint but rather weak hip abductors causing internal femur rotation [12].

PFPS is typically treated conservatively with the aim of reducing pain, improving monitoring of the patella, and re-establishing previous levels of function. Several studies have indicated that exercise is a beneficial treatment for individuals with PFPS [3,13]. Exercise is an effective treatment; indeed, it is the most extensively researched treatment, and it can specifically address the valgus malalignment that many individuals exhibit [4,13,14]. The forward lunge is a prevalent weight-bearing exercise that athletes and individuals with healthy knees use to train the hip and quadriceps muscles [15,16]. Physical therapists employ the forward lunge and other load-bearing exercises to restore knee function in patients afflicted with knee injuries and conditions, such as patellofemoral rehabilitation in individuals with PFPS [17].

Several studies have suggested that enhancing hip posture and performing quadriceps exercises can be beneficial for individuals suffering from patellofemoral pain syndrome [18,19]. Strengthening the hip adductors improves the therapeutic benefit of PFPS by increasing strength in the hip adductors. It is therefore recommended that hip adductor strengthening exercises be included in the management of PFPS. This, in turn, lengthens the VMO and alters its length–tension characteristics. As a result, the VMO performs better with increased positive contractile force. It is also important to note that technical terms will be explained when used for the first time [20]. Previous research conducted in the squatting position has demonstrated that the activation of hip flexors leads to a reduction in the strength of the VL, resulting in a greater degree of PFPS [21,22].

Numerous studies have investigated the efficiency of hip adduction forward lunge (HADF) and hip abduction forward lunge (HABF) for the treatment of PFPS [23–27]. Strengthening the VMO and VL through HADF and HABF, respectively, produces a therapeutic effect for PFPS. Hip adduction and abduction place pressure on the lateral and medial aspects of the knee, resulting in knee valgus and varus [27]; however, few studies have investigated this in combination with VMO and VL strengthening exercises. In this study, three forward lunge positions targeting hip placement were investigated to determine their effectiveness in reducing the risk of knee injury by measuring muscle activity along with changes in the center of pressure (CoP) of the foot. We hypothesized that the CoP changes and muscle activity in the hip neutral forward lunge (HNEF) position would be smaller than those in the hip adduction forward lunge (HADF) and hip abduction forward lunge (HABF) positions.

2. Materials and Methods

2.1. Participants

The sample size was estimated through an a priori power analysis carried out with the G* Power program (G power program Version 3.1, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany) assuming a univariate approach for the effects. In a preliminary study, a power of 0.81, an effect size (ES) of 0.82, and a significance level of 0.05 suggested a sample size of 18. To allow for a possible dropout rate of 10–20%, the projected sample size was set at 20. The recruitment for this study was conducted at the university between September and October 2022. Participants were excluded if they had the following: (1) current or previous knee injury or patellofemoral pathology; (2) pain in the knee during

recreational activities or during everyday activities, such as stepping forward, within the last three months; and (3) a BMI over 30. Participants were included if they were able to carry out forward lunge exercises without pain. The human subject's authorization form, approved by the university, was read and signed by all participants taking part in the study and they were informed of their right to withdraw. All participants also signed a consent form before the investigation proceeded. The Institutional Review Board at Daegu University granted approval for the study (approval number: 1040621-202207-HR-068).

2.2. Study Procedure

2.2.1. Study Design

Twenty participants were recruited for this study. Before the study commenced, the participants completed a standardized 5 min warm-up that entailed lunge forwards with a multi-plane movement of the hip. Then, they were provided with instructions to familiarize themselves with recording and practicing the measurements of CoP (position, sum distance, range, and max distance) and VMO and VL muscle activity so that they could execute the movements correctly. Then, while performing the HNEF, HADF, and HABF, both VMO and VL muscle activity and the CoP were recorded. Three repetitions of the three positions were performed in a randomized order. There was a 1 min rest between repetitions. A 5 min recovery period was included before assuming a new position to prevent muscle fatigue (Figure 1).
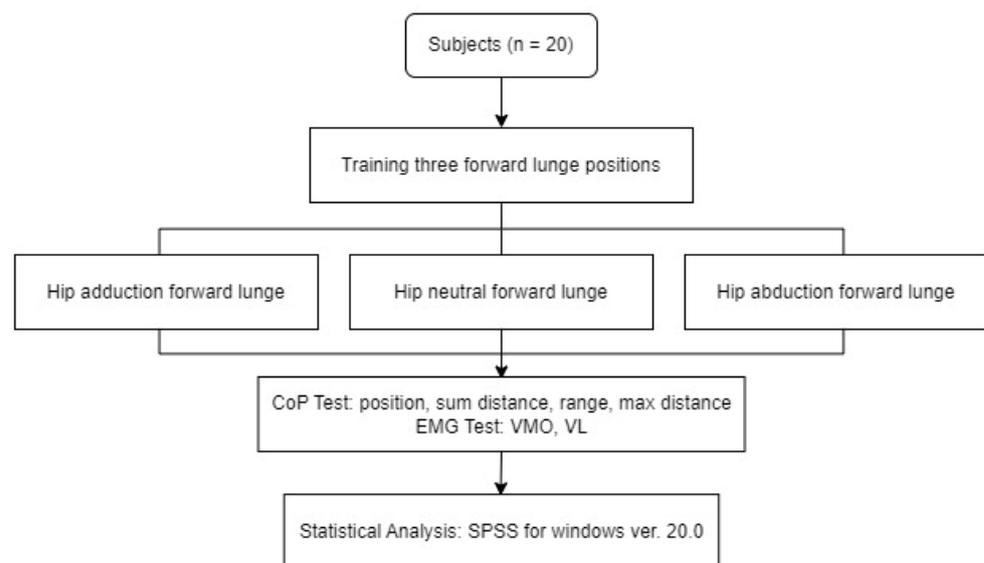

Figure 1. Study flow diagram.

2.2.2. Three Forward Lunge Positions

When standing on both legs, the participant was instructed to take a step forward with the dominant lower limb while flexing the knee joint to a 60° angle. The lower leg maintained a perpendicular position to the ground while producing peak hip adduction or abduction or neutral displacement, with no pelvic shift. Enabling the participants to carry out various hip adduction, abduction, and neutral motions prior to the assessment and inserting a guide plate into position helped ascertain the peak hip adduction, peak abduction, and neutral distances. The guide plate was touched by the subject during measurement to achieve peak hip adduction, peak abduction, and neutral distance. The opposite leg was extended, with the heel fixed to the ground. Then, the patient held their hands together over the chest and stood up straight, facing straight ahead.

2.3. Measurements

2.3.1. Measurement of CoP

A Balancia measuring device (version 2.0; Mintosys, Seoul, Republic of Korea) was used to assess the CoP of the three movements. The participant performed the forward lunge while placing their front leg on a "Wii Balance Board" (ICC = 0.71) and the back leg on a hard board of the same height. In measuring the CoP, we collected four types of data: position of the average CoP point on the frontal plane within 5 s (position); sum of the CoP positions at each time point on the frontal plane within 5 s at 0.01 s intervals (sum distance); the distance between the maximum and minimum of the CoP moving on the frontal plane within 5 s (range); and the maximum value of the CoP moving to the distance from the starting position on the frontal plane within 5 s (max distance). The position represents the size of the CoP moving on the frontal plane. The sum distance represents the direction and trend of the CoP moving on the frontal plane. The range represents the distance of the CoP from the medial to the lateral within the frontal plane. The max distance represents the distance at which the starting point is the standard and the distance away from the CoP reaches a maximum. Positive numbers represent the lateral direction in the frontal plane, and negative numbers represent the medial direction in the frontal plane.

2.3.2. Measurement of Muscle Activity

To quantify the muscle activity of the individual's VMO and VL, data were gathered using wireless surface electromyography (EMG) (TeleMyo DTS; Noraxon Inc., Scottsdale, AZ, USA). The sampling rate of the EMG signal was set to 1000 Hz, and the amplified waveform was filtered using a 40–400 Hz band pass filter and a notch filter to remove 60 Hz noise. To quantify all of the collected EMG signals, the root mean square (RMS) was processed, and the collected signals of each muscle were normalized as a percentage (% maximal voluntary isometric contraction; %MVIC) of the maximal voluntary isometric contraction. For each movement, electromyography signals were collected for five seconds. The initial and final seconds of the data were removed, leaving only a three-second analysis. Electromyography was recorded for three trials and the results were averaged. A one-minute break was permitted between each recording. The acquired data were expressed as a percentage of the root mean square of the maximum voluntary isometric contraction (%MVIC). A maximal voluntary isometric contraction (MVIC) test was performed before the participant assumed each of the three positions to ensure consistent measurement of the EMG signals from the postures. The knees were positioned against the edge of the platform, with the knees flexed at 90°. The participants were instructed to sit on an elevated platform without allowing their feet to touch the floor. Then, they were instructed to elevate their affected legs flexed to a knee angle of 60° and subsequently extend them to their fullest extent. Measurement of the maximum voluntary isometric contraction value of each muscle was performed 3 times for 5 s, and then the initial and final seconds were removed from the dataset. The average signal amount for these seconds was used. To prevent any movement and to facilitate a maximal isometric contraction of the knee extension, the examiner placed their hand on the ankle of the test leg. To avoid fatiguing the muscles, the evaluation was performed 3 times, resting for 2 min between each trial [28]. An electrode pad was situated 10 cm away from the patella using the connection line between the anterior superior pelvic spine and the outer edge of the patella for VL measurement. In addition, an electrode was positioned at a 50° angle along a straight line with respect to the parallel line running between the external patellar margin and anterior superior pelvic spines, 4 cm from the patella [29]. After completing the MVIC test, the participants were given a 5 min break before undergoing training in the 3 specific movements. The CoP and muscle activity measurements were performed simultaneously (Figure 2). Each position was repeated three times. There was a rest period of 1 min after each movement. The participants took a 5 min break after each position trial to minimize muscle fatigue.
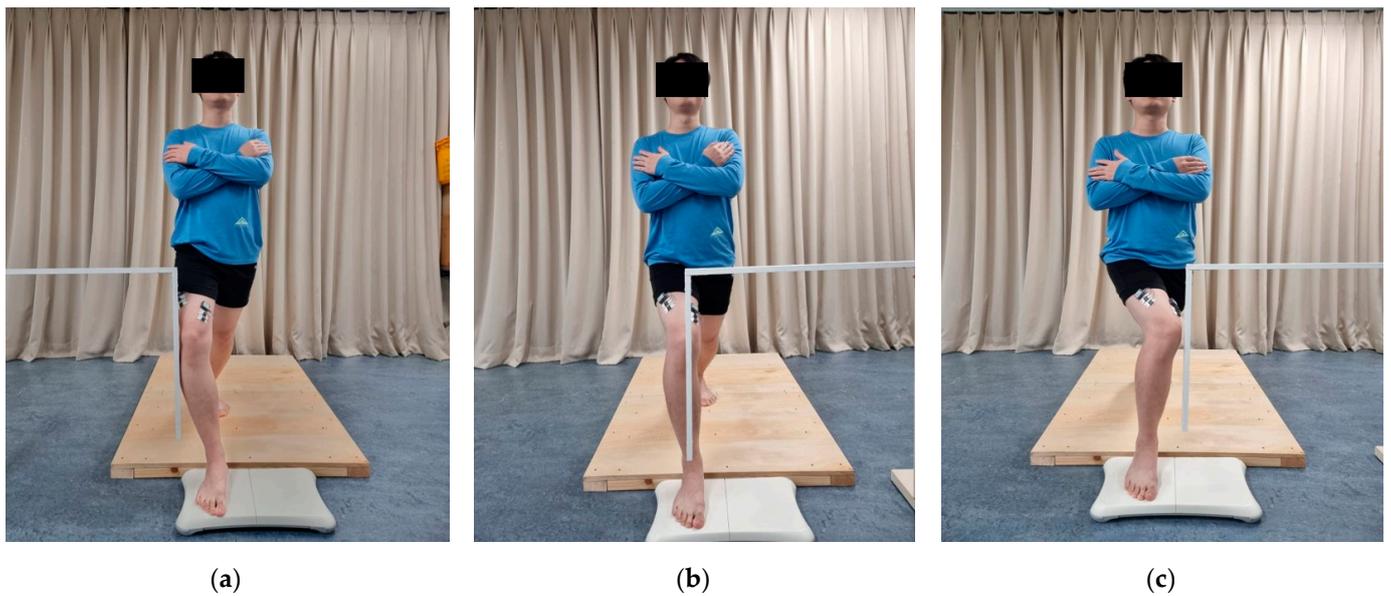
(**a**)   (**b**)   (**c**)

Figure 2. Measurement of CoP and muscle activity of VMO and VL: (**a**) hip abduction forward lunge; (**b**) hip neutral forward lunge; (**c**) hip adduction forward lunge.

2.4. Statistical Analysis

Statistics were analyzed using SPSS version 20.0 for Windows (SPSS, IBM Corp., Armonk, NY, USA). All data underwent a normal distribution test using the Kolmogorov–Smirnov method. To assess the difference in muscle activity and CoP, a one-way analysis of variance was conducted. The least-squares difference was determined as a post-test to explain the differences among the three positions after the test. Statistical significance was set at $p < 0.05$. The ES (Cohen d) was considered weak (ES = 0.1), intermediate (ES = 0.25), or strong (ES = 0.4).

3. Results

The general characteristics of the subjects are shown in Table 1. The average age was 23.7 years old (21–31 years), average height was 169.4 cm (158–185 cm), average weight was 64.35 kg (50–100 kg), and average body mass index (BMI) was 22.3 (19.53–29.22 kg/m^2).

Table 1. General characteristics of subjects.

Characteristics	Mean $\pm$ SD [1]
Age (yr)	23.7 $\pm$ 2.51
Height (cm)	169.4 $\pm$ 7.8
Weight (kg)	64.3 $\pm$ 12.7
Body mass index (kg/m^2)	22.26 $\pm$ 2.48

[1] Mean $\pm$ standard deviation.

The position (ES = 3.03), sum distance (ES = 3.05), range (ES = 6.31), and max distance (ES = 5.39) significantly ($p < 0.05$ unless stated otherwise) differed among the three positions. The outcomes of the CoP in the HADF were all negative values; in contrast, the outcomes of the CoP in the HABF and HNEF were positive values. Judging from the size of the numbers, the HABF produced significantly higher CoP outcomes than the HADF and HNEF in terms of position, sum distance, range, and max distance. The HNEF showed significantly higher CoP outcomes than the HADF (Table 2) (Figure 3).

Table 2. Comparison of variation in CoP between three positions.

	HADF [1]	HNEF [2]	HABF [3]	F	*p*	ES [4]
position (cm)	−0.85 ± 0.80	0.02 ± 0.38	0.98 ± 0.55	48.325	0.001 *	3.03
sum distance (cm)	−428.34 ± 399.33	10.44 ± 189.78	488.97 ± 276.76	48.739	0.001 *	3.05
range (cm)	−2.28 ± 0.62	1.52 ± 0.77	2.25 ± 0.75	240.859	0.001 *	6.31
max distance (cm)	−1.85 ± 0.76	0.66 ± 0.57	1.89 ± 0.73	158.708	0.001 *	5.39

[1] Hip adduction forward lunge. [2] Hip neutral forward lunge. [3] Hip abduction forward lunge. [4] Effect size.
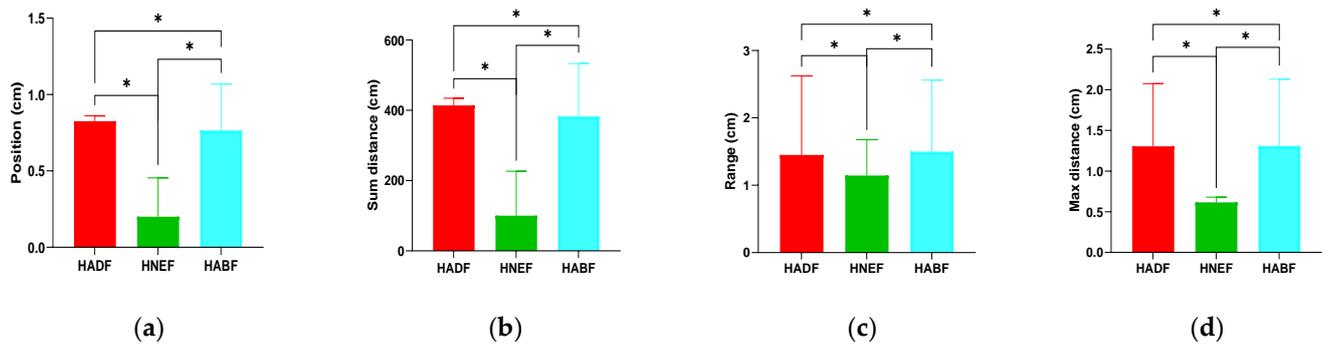* Significant difference between groups ($p < 0.05$).

Figure 3. Comparison of variation in CoP between three positions: (**a**) position; (**b**) sum distance; (**c**) range; (**d**) max distance. * Significant difference between groups ($p < 0.05$).

The movement trajectories of the CoP for the three postures within 5 s at intervals of 1 ms showed that most of the outcomes of the CoP in the HADF were negative numbers; on the contrary, most of the CoP outcomes in the HABF were positive numbers. The movement trajectories of the CoP in the HNEF first analysis showed negative numbers and then positive numbers (Figure 4).
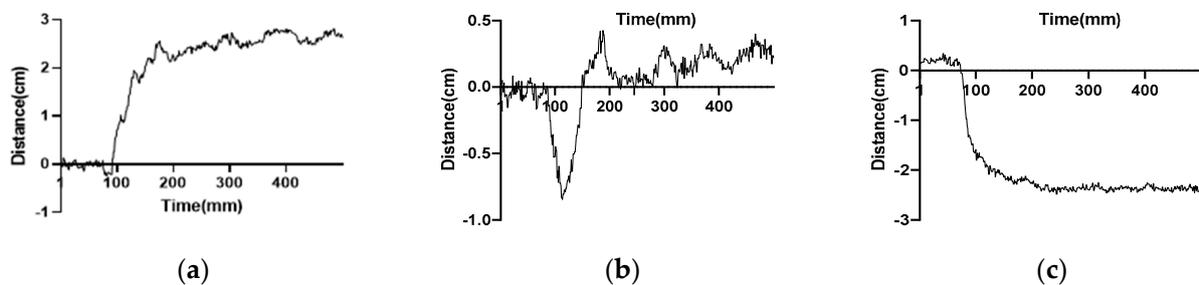

Figure 4. Example of movement trajectory of CoP within five seconds: (**a**) hip abduction forward lunge; (**b**) hip neutral forward lunge; (**c**) hip adduction forward lunge.

The VMO (ES = 1.71) and VL (ES = 0.53) muscle activity and the ratio of VMO/VL (ES = 1.27) significantly differed among the three positions. In the VMO, the HADF produced significantly higher muscle activity (58.30 ± 14.42% MVIC) than the HABF and HNEF. The HABF (45.28 ± 16.23% MVIC) showed significantly higher muscle activity than the HNEF (34.88 ± 9.49% MVIC). In the VL, the HABF produced significantly higher muscle activity (48.44 ± 16.19% MVIC) than the HADF and HNEF. The HADF (40.98 ± 12.64% MVIC) showed significantly higher muscle activity than the HNEF (33.79 ± 11.57% MVIC). In the ratio of VMO/VL, the HADF produced significantly higher muscle activity (1.48 ± 0.31) than the HABF and HNEF. In addition, the HNEF (1.11 ± 0.33) showed significantly higher muscle activity than the HABF (0.96 ± 0.23) (Table 3) (Figure 5).

Table 3. Comparison of muscle activity of VMO and VL between three positions.

	HADF [1]	HNEF [2]	HABF [3]	F	p	ES [4]
VMO (%MVIC) [5]	58.30 ± 14.42	34.88 ± 9.49	45.28 ± 16.23	14.721	0.000 *	1.71
VL (%MVIC) [6]	40.98 ± 12.64	33.79 ± 11.57	48.44 ± 16.19	5.791	0.005 *	0.53
Ratio [7]	1.48 ± 0.31	1.11 ± 0.33	0.96 ± 0.23	16.745	0.000 *	1.27

[1] Hip adduction forward lunge. [2] Hip neutral forward lunge. [3] Hip abduction forward lunge. [4] Effect size. [5] Vastus midialis obliques. [6] Vastus lateralis. [7] Muscle activity of vastus midialis obliques/muscle activity of vastus lateralis. * Significant difference between groups ($p < 0.05$).
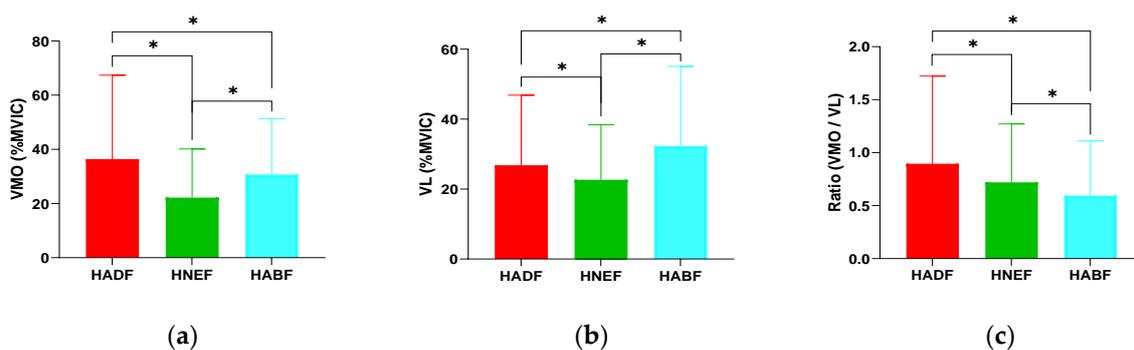

Figure 5. Comparison of muscle activity of VMO and VL between three positions: (**a**) muscle activity of VMO; (**b**) muscle activity of VL; (**c**) ratio of muscle activity of VMO/VL. * Significant difference between groups ($p < 0.05$).

4. Discussion

We investigated the effect of the HADF, HABF, and HNEF on changes in the CoP and quadriceps muscle activity. Our results are in line with those of previous studies, in that the quadriceps activity and the change in the CoP significantly increased for the HADF and HABF compared to the HNEF.

Based on the position and sum distance results, the CoP of the HABF moved laterally in the frontal plane, that of the HADF moved medially in the frontal plane, and that in the frontal plane for the HNEF moved minimally to zero. An alternative explanation could be a biomechanical one; specifically, when the hip joint was adducted, the lower limb moved medially, and the resulting position was reflected medially. Similarly, when the hip joint was abducted, the lower limb moved laterally, and the resulting position was reflected laterally [30]. Because the forward lunge is a closed kinetic chain movement, the foot is immobilized when the hip is internally adducted. This causes the knee to move medially, creating a variable amount of pressure at the lateral aspect of the patellofemoral joint. At the same time, such a movement increases the risk of developing knee valgus [31,32]. Similarly to this is the danger of knee inversion that occurs when the hip is abducted. Compared to the HABF and the HADF, evidence implies that the HNEF is more beneficial for the patellofemoral joint. According to the results of assessments of the CoP, the HNEF showed a slight lateral movement in the coronal plane, which may be explained by the fact that the CoP was in the middle of the legs during the onset of the movement. After the forward lunge, the CoP shifted forward toward the flexed leg. Because all of our subjects were right-leg dominant, the CoP of the HNEF would have shown a slight lateral movement in the coronal plane. Compared to the other two exercises, the HNEF added little significant knee valgus pressure and thus was less likely to produce valgus and varus pressures. The results of the range and max distance assessments showed that the CoP range of displacement and the maximum distance of movement in the HADF and HABF were significantly larger than those of the HNEF on the medial and lateral sides of the frontal plane. The HADF and HABF may produce a noticeable medial and lateral expansion of the knee joint so that there is a greater distance compared to the HNEF [30].

At the same time, the range values were larger than the max distances. This suggests that the movement trajectory of the CoP does not change continuously in one direction. There was

a process of reverse movement for all three positions that was larger in the HNEF than in both the HADF and HABF. The smaller reverse movement in the latter two may have been due to wobbling of the ankle joint from the adaptation process in response to the increased stress at the beginning of the forward lunge [33]. The larger reverse movement in the HNEF may have been caused by unconscious hip adduction occurring at the beginning of the movement.

For the EMG of the VMO, there were significant differences among the three positions. The muscle activity of both the HADF and HABF were more effective than the HNEF, and the HADF was the most effective position. This behavior is in accordance with theories reported in the literature. According to Miao et al. [34], hip adduction dilates the VMO muscle, changing its tension–length characteristics such that a greater contraction force is produced. The three adductor muscles (the longus, magnus, and brevis) make up the adductor complex [35]. From the adductor magnus tendon, the distal part of the vastus medialis (VM) muscle is derived [36]. The VM muscle has two components, VML and VMO, which differ in their orientation angle of muscle fibers [36]. According to Kumar et al. [24], strong hip adapters provide a stable origin for the VMO. Thus, when adducting the hip, the VMO participates in the motion. Greater muscle activity of the VMO was observed in the HADF condition. Mechanically, the HADF could lead to increased femoral adduction and medial rotation, which would increase the lateral patellofemoral joint vector, leading to patellar facet overload [37]. In cases of dysregulated motor control, individuals fail to engage in appropriate muscle activation during rapid movements (e.g., changes in direction, jumping), which results in the loss of knee joint stability and an increased risk of adduction. Long-term neurological control deficits (such as poor posture or strength imbalances) may make individuals more susceptible to exhibiting poor movement patterns during exercise, further increasing the likelihood of knee adduction.

At the same time, there were significant differences in the EMG of the VL among the three positions. The muscle activity was highest while performing each lunge, with that of the HADF being higher than that of the HNEF. This confirms that hip abduction exercises can improve hip abductor muscle activity [24,31], as reported in the literature. According to Chen et al. [27], the lateral patellar vector increases during hip abduction due to increased VL muscle activation. For the agonist muscle to be able to provide resistance and produce movement, there must be muscular co-contraction to stabilize the motion. However, if certain muscle groups are underactive (such as a weakening of the vastus medialis), or if certain muscle groups are overactive (such as an overactive vastus lateralis), knee adduction may occur. In a systematic study, Santos et al. [38] discovered that strengthening the hip abductor muscles successfully lowers discomfort and enhances function. By performing exercises focused on the forward lunge with hip abduction, motor control can be re-established, resulting in less controlled knee movements and the onset of knee valgus in functional tasks [23]. Due to the potential for patellar lateralization, Escamilla et al. [39] propose that exercise training regimens for PFPS should avoid movements heavily activating the VL.

It is important to acknowledge the limitations of our study. The hip joint's range of motion was not considered, and we did not assess the activity of the frontal plane muscles of the hip. Furthermore, our study participants were young and healthy, and our results may not apply to other groups. More studies are needed to determine the effects of the HNEF on the CoP and quadriceps muscle activity in normal subjects and PFPS patients.

5. Conclusions

The forward lunge is an exercise used to strengthen the quadriceps muscle. In this study, the HADF was the best for activating the quadriceps; however, this exercise increased the valgus pressure of the knee joint thereby increasing the risk of knee valgus. The HNEF may be beneficial in terms of reducing the risk of injury while exercising. In addition, the HNEF should be carried out with active control to prevent unconscious medial movement of the knee joint.

Author Contributions: Conceptualization, X.-H.Z.; methodology, T.-H.K.; software, X.-H.Z., X.Y. and Q.-S.T.; validation, X.-H.Z., X.Y., Q.-S.T. and T.-H.K.; formal analysis, X.-H.Z., X.Y. and Q.-S.T.;

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