Force generation and neuromuscular activity in multi-joint isometric exercises: comparison between unilateral and bilateral stance

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Abstract The purpose of the present study was to look at lower extremity force generation and neuromuscular activation by comparing isometric mid-thigh pull in the unilateral stance (IMTP_{Uni}) and bilateral stance (IMTP_{Bi}), and identifying the characteristics of IMTP_{Uni}. Fifteen male collegiate athletes (age: 20.60 ± 1.50 years, height: 1.74 ± 0.05 m, mass: 69.04 ± 4.23 kg) performed IMTP_{Uni} and IMTP_{Bi} as multi-joint isometric exercise. Ground reaction force (GRF) was measured to assess force generation during IMTP. Surface electromyography (EMG) was used to measure neuromuscular activation in the gluteus maximus ($G_{\max}$), gluteus medius (G_{med}), semitendinosus, biceps femoris (BF), rectus femoris (RF) and vastus lateralis (VL), which were represented as average rectified values (ARVs). The EMG of the muscles during IMTP_{Uni} was normalized by IMTP_{Bi} to compare relative change among muscles. The co-contraction index (CI) during IMTP_{Uni} was also calculated by using normalized EMG. As a result, IMTP_{Bi} was significantly higher in BF than IMTP_{Uni}. However, in IMTP_{Uni}, although only one leg contributed to produce force, GRF of IMTP_{Uni} reached 80% of neuromuscular activity relative to IMTP_{Bi}. While the neuromuscular activation of $G_{\max}$, G_{med} , BF, RF and VL was significantly higher proportionately in IMTP_{Uni} compared to IMTP_{Bi}, neuromuscular activation was even greater in $G_{\max}$ and G_{med} . The co-contraction index (CI) was increased in IMTP_{Uni}. The features of neuromuscular activation during IMTP_{Uni} were similar to the single leg squat and step-up exercise examined in previous studies due to the necessity to support the body with a single leg.

Keywords : isometric exercise, unilateral stance, IMTP, neuromuscular activation

Introduction

Multi-joint exercises, rather than single joint exercises, are generally recommended to assess the strength of athletes, as athletic movements are mostly composed of multi-joint actions^{1,2)}. Therefore, multi-joint exercises are preferentially incorporated into resistance training programs for athletes. Multi-joint exercises with unilateral stance are also available and effective for athletes who need rehabilitation after injuries³⁾. As the base of support is reduced for unilateral stance exercises compared to bilateral stance exercises, the former is less stable than the latter. In unilateral stance, the hip abductors and hamstrings contribute to maintain balance by enhancing stability at the hip and knee joints^{4,5)}. Previously, McCurdy et al.⁶⁾ clarified that the neuromuscular activation of gluteus medius (G_{med}) and hamstrings in single leg squats was significantly greater than in double leg squat. Furthermore, Ebben et al.⁷⁾ also demonstrated that the activ-

ity of hamstrings and rectus femoris (RF) was greater in step-up exercise, a form of unilateral stance exercise, than in double leg squat and deadlift. Indeed, previous studies demonstrated that more muscles were able to be recruited without reduction of strength exertion during unilateral stance exercise^{8,9)}. On the other hand, co-contraction, which is the simultaneous activation of agonist and antagonist around a joint, contributes to maintaining balance¹⁰⁾. Especially concerning knee flexion and extension muscles, it is speculated that these muscles are activated in this manner during unilateral stance exercise¹¹⁾.

The isometric mid-thigh pull (IMTP) in the unilateral stance (IMTP_{Uni}) is an alternative to unilateral multi-joint exercises and it is known to be a relatively safe method for muscle strength assessment¹²⁾. Previously, Thomas et al.⁸⁾ reported that variables of the IMTP_{Uni} significantly correlated with sprint time, but variables of the IMTP in the bilateral stance (IMTP_{Bi}) did not. However, they didn't demonstrate objective evidence as to why IMTP_{Uni} can be a predictor of sprint time. Based on these results, it's possible that IMTP_{Uni} recruits and coordinates muscles

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in a different manner even though the same movement is performed using a single leg as that which is performed in IMTP_{Bi} using both legs. It is important to identify the characteristics of IMTP_{Uni} in terms of neuromuscular activation pattern. To our knowledge, however, no study has previously examined the surface electromyography (EMG) of muscles during IMTP_{Uni}. As mentioned above, as close kinetic chain exercise with single leg stance would increase the number of muscles recruited and augment muscle activation^{6,7)}, it is impossible to reveal the characteristics of IMTP_{Uni} without examining the EMG of each muscle. Therefore, the purpose of the present study was to compare force generation and neuromuscular activation of the lower extremity between IMTP_{Uni} and IMTP_{Bi} for identifying the characteristics of IMTP_{Uni}. Also, we aimed to compare the relative changes of neuromuscular activation from IMTP_{Bi} to IMTP_{Uni} among muscles and examine the co-contraction index (CI) during IMTP_{Uni}. The hypothesis of the present study was that muscles around a hip joint would be activated particularly in IMTP_{Uni}, because it is required to support the pelvis due to single leg stance. The results of the present study could provide evidence of how unilateral isometric exercise could be used in training and rehabilitation.

Materials and Methods

Participants. Fifteen male collegiate athletes (age: 20.60 ± 1.50 years, height: 1.74 ± 0.05 m, body mass: 69.04 ± 4.23 kg) volunteered for this study. They were screened for injuries that could affect the performance of the isometric exercises. Information regarding this study was provided to all individuals prior to participation. The Ethics Committee for the Institute of Health and Sport Sciences, University of Tsukuba, approved all procedures (approval number: 28-10).

Measures. In the present study, IMTP was used as a multi-joint isometric exercise. Participants performed IMTP_{Bi} and IMTP_{Uni} during the same testing session. The ground reaction force (GRF) and surface electromyography (EMG) of the lower extremities were simultaneously measured during IMTP_{Bi} and IMTP_{Uni}. For EMG, neuromuscular activation of the gluteus maximus ($G_{\max}$), G_{med} , semitendinosus (ST), biceps femoris (BF), RF, and vastus lateralis (VL) were assessed. The neuromuscular activation was evaluated by EMG. All participants practiced IMTP_{Bi} and IMTP_{Uni} before IMTP testing, which was separated by over 48 hours.

IMTP Testing. The participants performed IMTP_{Bi} by standing on two force plates sized 0.6×0.6 m (Ex-Jumper, DKH, Tokyo, Japan) to collect the GRF in a custom-designed power rack. Lifting straps and athletic tape were used to remove the influence of grip strength. It was verified that the knee and hip angles fell to 120° and

140° , respectively¹³⁾. Moreover, instruction was provided so participants would keep the trunk in an upright position¹⁴⁾. For IMTP_{Uni}, the knee and hip angles of the stance leg and trunk position were also standardized as well as in the IMTP_{Bi}. The knee angle of the unsupported leg during IMTP_{Uni} was to be held at 90° , and a swinging motion was prohibited¹⁵⁾. After general and specific warm-up, the participants performed IMTP_{Bi}. After that, IMTP_{Uni} was performed in the right leg and left leg in a randomized order. Two practice attempts at 50% and 75% of each participant's perceived maximum effort were performed before IMTP_{Bi} and IMTP_{Uni} as a warm-up¹⁶⁾. Participants were instructed to pull the bar as hard and fast as possible for four seconds.

EMG. Participant hair was shaved at the site of the EMG electrode placement, and the skin was also cleaned with alcohol before placing the electrode. Bipolar silver/silver-chloride active bar electrodes were used to record EMG signal (Nihon Kohden, Tokyo, Japan). The bar electrodes were 10-mm length and 2-mm width, and two bar electrodes were attached on both legs with the contact surfaces in longitudinal alignment with the muscle fibers and at an inter-electrode distance of 20-mm. The EMG signals were bandpass-filtered between 10 and 500 Hz. In off-line processing, the placement of the EMG electrodes on each muscle was determined in accordance with the SENIAM protocol, which is the global standard for collecting EMG data¹⁷⁾.

Data Analysis. For IMTP_{Bi}, vertical GRF was sampled at 1000 Hz on each leg¹⁸⁾. The total GRF of the right and left legs was used to determine the onset of the pull as the point when GRF was achieved at 105% of participant body weight. Force outputs were calculated based on GRF sampling at peak force (PF) during four seconds of pulling¹⁶⁾. This variable has been used to evaluate maximum strength in a previous study^{14,16,19)}. The variable was calculated as absolute GRF minus participant body weight¹⁹⁾. For IMTP_{Uni}, the PF was also determined based on the vertical GRF sampled on the stance leg. Testing attempts were performed three times for IMTP_{Bi} and IMTP_{Uni}, and the order of the right and left legs in IMTP_{Uni} was randomized. The top two PF trials were selected from the three trials and averaged for further analysis. For IMTP_{Uni}, the stronger leg, which was determined by a larger PF value between the leg trials, was used to analyze GRF and muscle activity. The test-retest reliability for force outputs met the standard for reliability of IMTP variables, which was intra-class correlation coefficient (ICC) > 0.70 ²⁰⁾.

All EMG signals sampled at 1000 Hz were analyzed. GRF and raw data of EMG for each muscle during IMTP_{Bi} and IMTP_{Uni} are shown in Fig. 1. Neuromuscular activation during IMTP_{Bi} and IMTP_{Uni} were represented as average rectified value (ARV) which was averaged in two time periods to ensure consistency with the force vari-

ables like PF. Specifically, it was averaged EMG data 100 milliseconds (ms) before and after the point when PF was achieved on GRF. Moreover, EMG during IMTP_{Uni} was normalized by IMTP_{Bi} because the joint angles of those exercises were the same. By using the normalized EMG, the relative change in neuromuscular activation was compared from bilateral stance to unilateral stance among the muscles.

In the present study, the co-contraction index (CI) was analyzed to investigate stability in the knee joint during IMTP_{Uni}. Normalized EMG was used to determine the CI. The neuromuscular activation of knee flexors (K_{flex}) was calculated as the averaged value of ST and BF. While, the neuromuscular activation of knee extensors (K_{ext}) was cal-

culated as the average value of RF and VL. The formula of the CI is shown here as used in a previous study¹¹⁾:

$$\text{Co-contraction index (CI)} = (K_{flex} + K_{ext}) * (EMG_{\text{Smaller}} / EMG_{\text{Greater}}).$$

where, EMG_{Smaller} is the smaller value of K_{flex} and K_{ext} , and EMG_{Greater} is the greater value of them. Since the greater value between K_{flex} and K_{ext} is dependent on the individual, the definition such as “Smaller” and “Greater” is used in the formula¹¹⁾.

Statistical Analysis. Descriptive analysis was represented as mean and standard deviation (SD). ICC was used to evaluate for within-session test-retest reliability of force

Fig. 1 Ground reaction force and raw data of EMG of each muscle during bilateral and unilateral stance IMTP.

output and EMG. The normality test of data was analyzed by Shapiro-Wiki. For PF, the paired t-test was used to determine the difference of the PF between IMTP_{Bi} and IMTP_{Uni}. For neuromuscular activation in the lower extremities, Wilcoxon signed rank test was used to compare IMTP_{Bi} and IMTP_{Uni}. On the other hand, the Friedman test was performed to analyze the significant difference among muscles in normalized EMG during IMTP_{Uni}, and Wilcoxon signed rank test was selected as a post-hoc test. Cohen's d value was calculated based on the mean and SD to show practical significance. All statistical analysis was performed using SPSS v22 software (IBM, New York, USA). The criterion for statistical significance was considered as $p < 0.05$.

Results

The descriptive data for PF is shown in Table 1. As a result of the normality test by Shapiro-Wiki, PF had a normal distribution. As a result of comparing PF, IMTP_{Bi} was significantly higher than IMTP_{Uni} ($p < 0.05$, $d = 0.94$). Although the PF was significantly higher in IMTP_{Bi} than in IMTP_{Uni}, IMTP_{Uni} could be achieved at 83% relative to IMTP_{Bi}.

The descriptive data and the ICC in each muscle during IMTP_{Bi} and IMTP_{Uni} are shown in Table 2. Indeed, a comparison of ARV between IMTP_{Bi} and IMTP_{Uni} for each muscle is shown in Fig. 2. As the result of the normality test by Shapiro-Wiki, most of the variables in neuromuscular activation were not a normal distribution. Therefore, the Wilcoxon signed rank test was employed to compare neuromuscular activation between IMTP_{Bi} and IMTP_{Uni} as a non-parametric test. As a result, the Wilcoxon signed rank test revealed that neuromuscular activation of the lower extremities in IMTP_{Uni} was significantly greater than IMTP_{Bi} in $G_{\max}$ ($p < 0.05$, $d = 1.14$), G_{med} ($p < 0.05$, $d = 0.65$), BF ($p < 0.05$, $d = 0.48$), RF ($p < 0.05$, $d = 0.98$), and VL ($p < 0.05$, $d = 0.87$).

As a result of the normality test by Shapiro-Wiki, most of the variables were not a normal distribution as well as unnormalized EMG. Therefore, the Friedman test and Wilcoxon signed rank test were performed to compare normalized EMG among muscles as a non-parametric test. The result of the comparison is shown in Fig. 3, in which $G_{\max}$ and G_{med} were significantly greater than RF and VL ($p < 0.05$).

The CI during IMTP_{Uni} was analyzed, which was 229.71 for mean and 97.64 for SD. It was not possible to com-

Table 1. Descriptive analysis and comparison for force output.*

Variable	IMTP _{Bi}	IMTP _{Uni}	Paired t-test	
	Mean $\pm$ SD	Mean $\pm$ SD	Significance	Cohend's d
PF (N)	2021.54 $\pm$ 435.08	1674.13 $\pm$ 286.00	†	0.94

* †; significant difference ($p < 0.05$).

Table 2. Descriptive analysis of ARV and ICC in each muscle.*

	Bilateral stance IMTP		Unilateral stance IMTP	
	Mean $\pm$ SD	ICC	Mean $\pm$ SD	ICC
PF (mV)				
$G_{\max}$	0.054 $\pm$ 0.037	0.762	0.111 $\pm$ 0.060	0.887
G_{med}	0.071 $\pm$ 0.069	0.724	0.148 $\pm$ 0.153	0.987
ST	0.054 $\pm$ 0.048	0.886	0.066 $\pm$ 0.033	0.746
BF	0.065 $\pm$ 0.061	0.830	0.092 $\pm$ 0.051	0.894
RF	0.016 $\pm$ 0.007	0.924	0.025 $\pm$ 0.011	0.975
VL	0.059 $\pm$ 0.033	0.897	0.101 $\pm$ 0.060	0.966

* ICC; Intra-class correlation coefficient.

Fig. 2 A comparison between bilateral and unilateral stance IMTP in ARV for each muscle.
Footnotes: G_{max}; gluteus maximus, G_{med}; gluteus medius, ST; semitendinosus, BF; biceps femoris, RF; rectus femoris, VL; vastus lateralis.
†; significant difference ($p < 0.05$).

Fig. 3 A comparison of normalized EMG among muscles during IMTP_{Uni}.
Footnotes: G_{max}; gluteus maximus, G_{med}; gluteus medius, ST; semitendinosus, BF; biceps femoris, RF; rectus femoris, VL; vastus lateralis.
†; significant difference from RF ($p < 0.05$).
‡; significant difference from VL ($p < 0.05$).

pare significantly between IMTP_{Uni} and IMTP_{Bi} in CI for the knee joint because neuromuscular activity during IMTP_{Uni} was normalized by that of IMTP_{Bi} as 100%. When 100% of neuromuscular activity in IMTP_{Bi} is substituted to the formula of the CI, the co-contraction index during IMTP_{Bi} can be calculated as 200. Therefore, the co-contraction index during IMTP_{Bi} was used as a reference value which was calculated as 200.

Discussion

Therefore, the purpose of the present study was to compare force generation and neuromuscular activation of lower extremity between IMTP_{Uni} and IMTP_{Bi} for identifying the characteristics of IMTP_{Uni}. Also, we aimed to compare the relative changes in neuromuscular activation between IMTP_{Bi} to IMTP_{Uni} among muscles and examine

the CI during IMTP_{Uni}. In this study, we chose the IMTP_{Uni} as unilateral stance isometric exercise, since IMTP_{Uni} is becoming a general tool to safely evaluate muscle strength in detail¹⁵. Furthermore, there is a significant correlation between the variables of IMTP_{Uni} and sprint time⁹.

Our results revealed that the PF was larger in bilateral stance exercise than in unilateral stance exercise. However, in IMTP_{Uni}, even though only one leg contributed to producing force, GRF of IMTP_{Uni} achieved 80% of GRF of IMTP_{Bi}. Similarly, Thomas et al.⁹ demonstrated that IMTP_{Uni} could achieve approximately 90% of the force generation of the bilateral stance, whereas another previous study demonstrated that the force exerted by a single leg during a knee extension exercise was approximately 60% of the bilateral stance⁸. Although both studies demonstrated that unilateral stance exercise could achieve more than 50% of the force production as compared with bilateral exercise, the results of the present study and that of Thomas et al.⁹ demonstrated that the increment ratios were much larger in IMTP than knee extension. The difference between these studies might be associated with the form of exercise: knee extension exercise is classified as an open kinetic chain exercise, whereas IMTP_{Uni} is classified as a closed kinetic chain exercise, as the leg is fixed on the ground during activity.

In addition to augmentation of PF, the surface EMG measurement of the present study demonstrated that the activity of $G_{\max}$ and G_{med} in IMTP_{Uni} was significantly increased compared to IMTP_{Bi}. While, normalized EMG in $G_{\max}$ and G_{med} was significantly greater than RF and VL. These results could mean that the magnitude of relative change of neuromuscular activation is different depending upon the muscle. Moreover, the relative changes of neuromuscular activation in gluteus muscles during IMTP_{Uni} were well over 200%, 243.21% in $G_{\max}$ and 280.10% in G_{med} . Especially in the case of G_{med} , it was activated almost three times more in IMTP_{Uni} than IMTP_{Bi}. These results indicate that the gluteus muscles were activated in a different manner during IMTP_{Uni} compared to IMTP_{Bi}, and these results support our hypothesis. The possible reason why $G_{\max}$ and G_{med} were more activated in IMTP_{Uni} might be associated with unstable body balance, as the legs are fixed on the ground with a single leg stance instead of both legs during IMTP_{Uni}, making the whole body unstable. The increments in $G_{\max}$ and G_{med} activation are likely due to the effort of the body to regain the balance lost due to the reduced base of support. In such a situation, specifically, $G_{\max}$ and G_{med} contribute to disturbing the drop down of the pelvis and the attempt to maintain the balance of the pelvis by elevating its opposite side. In a previous study, Crossley et al.³ used a dynamometer to demonstrate that participants who were superior in a single leg squat task were stronger in hip adduction torque compared to participants who were inferior. Thus, in single leg squat, they argued that the $G_{\max}$ and G_{med} play

an important role in stabilizing the balance of the pelvis in closed kinetic chain exercise with unilateral stance. Additionally, during exercise with unilateral stance, the hip abductors laterally elevate the pelvis on the side of the unsupported leg to prevent losing whole-body balance²¹. Elevating the pelvis on the side of the unsupported leg would push the opposite side of the pelvis down, which would cause the vertical component of GRF²². Accordingly, based on the significant increment of neuromuscular activation in $G_{\max}$ and G_{med} , the lateral elevation of the pelvis contributes to the incremental vertical component of GRF in unilateral stance isometric exercise.

Another novel finding of surface EMG in the present study is that neuromuscular activities of BF, RF and VL were augmented during IMTP_{Uni} compared to IMTP_{Bi}. Especially, increased neuromuscular activity of BF was able to contribute to increased knee stability in closed kinetic chain exercises²³. Regarding the unilateral stance exercises, it was suggested that hamstring activity increased during the single leg squat and step-up exercises compared to double leg squat and deadlift because of increased knee instability due to a reduced support base^{6,7}. McCurdy et al.⁶ revealed significant augmentation of hamstrings in single leg squat relative to double leg squat exercise; and this finding supports our results about neuromuscular activation of BF. The simultaneous activation of agonists and antagonists contributes to increased knee joint stability, which has been known as co-contraction⁵. Although a significant comparison of the co-contraction index (CI) between IMTP_{Uni} and IMTP_{Bi} could not be performed in the present study, mean value of the CI during IMTP_{Uni} was much higher than a referent value of IMTP_{Bi}. From the perspective of anatomy, a high CI would be associated with knee stability in extension/flexion and varus/valgus^{10,23}. Therefore, IMTP_{Uni} would activate the hamstrings and quadriceps femoris to augment joint stability at the knee through co-contraction. Accordingly, the results of the present study suggest that unilateral stance isometric exercise is also characterized by using the co-contraction of muscles around the knee joint as well as hip abductors. This stabilization via recruitment of hip abductors and co-contraction of BF, RF and VL could be associated with running performance and change-of-direction tasks^{22,24,25}.

Limitations in the present study include that we did not examine the surface EMG of upper body muscles. It is assumed that upper body muscles, such as the trapezius and elector spinae, could also produce force during IMTP. Further investigation should be performed to examine possible differences in upper body muscles during unilateral and bilateral stances. While only the EMG of muscles was investigated in the present study, it would be difficult to quantify the number of recruited muscles. Therefore, an additional analysis of examining motor unit firing properties during IMTP_{Uni} might be effective for this research area. Additionally, there was a limitation regarding the CI. Although a significant comparison of the

co-contraction index (CI) between IMTP_{Uni} and IMTP_{Bi} could not be performed in the present study, it would be preferable to compare the CI to clarify its increase during IMTP_{Uni}.

In conclusion, the results of the present study were that the force generation and neuromuscular activation of G_{max}, G_{med}, BF, RF and VL were increased in IMTP_{Uni} compared to IMTP_{Bi}. Also, a comparison of relative change of neuromuscular activation among muscles revealed that G_{max} and G_{med} were more significantly activated than RF and VL, showing that, in particular, the muscles around a hip joint would be activated. Moreover, analysis of the CI using normalized EMG suggested that co-contraction around a knee joint would be more enhanced during IMTP_{Uni} compared to IMTP_{Bi}. The features of neuromuscular activation during IMTP_{Uni} were similar to the single leg squat and step-up exercise in previous studies due to the necessity of supporting the body with one leg. Therefore, unilateral stance isometric exercise like IMTP_{Uni} could be incorporated into a series of exercises, using a single leg in rehabilitation and training, to learn how to enhance stability through activating the muscles around the hip and knee joint.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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