Asymmetry of force generation and neuromuscular activity during multi-joint isometric exercise

Seita Kuki1*, Yu Konishi2, Masamichi Okudaira1, Takuya Yoshida3, Tim Exell4 and Satoru Tanigawa3

1 Graduate School of Comprehensive Human Science, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8574, Japan
2 Department of Physical Education, National Defense Academy, 1-10-20 Hashirimizu, Yokosuka, Kanagawa 239-8686, Japan
3 Faculty of Health and Sports Science, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8574, Japan
4 Department of Sport and Exercise Science, University of Portsmouth, University House, Winston Churchill Ave, PO1 2UP Portsmouth, UK

Received: May 8, 2018 / Accepted: October 15, 2018

Abstract The purposes of the present study were (a) to determine whether a self-reported dominant leg was consistent with a dominant leg of force generation by using the isometric mid-thigh pull (IMTP) tests and (b) identify the features of bilateral IMTP (IMTPbi) and unilateral IMTP (IMTPuni) in terms of detecting strength imbalance of athletes. Fifteen male collegiate athletes performed IMTPuni and IMTPbi. The ground reaction force and surface electromyography were sampled with 1000Hz to assess force generation and neuromuscular activities in the gluteus maximus (Gmax), gluteus medius (Gmed), semitendinosus (ST), biceps femoris (BF), rectus femoris (RF) and vastus lateralis (VL) during IMTP. Legs were separated into dominant and non-dominant leg categories in accordance with two types of definitions including self-reported dominance of kicking leg and dominance of force generation in IMTP. In force generation and neuromuscular activity of IMTPbi and IMTPuni, there was no significant difference between self-reported dominant and non-dominant leg. However, results for a self-reported dominant leg were not consistent with results for dominant leg determined by force generation. In addition, the dominant leg of force generation exerted significantly larger PF than non-dominant leg, and the magnitude of asymmetry in IMTPbi was significantly larger than that of IMTPuni. Moreover, in IMTPuni, the neuromuscular activity of the VL of the dominant leg of force generation was significantly larger than that of the non-dominant leg. Therefore, it was suggested the necessity to distinguish the two types of IMTP tests because of the possibility that the strength imbalances detected by IMTPuni and IMTPbi would have different connotations.

Keywords: strength imbalance, asymmetry, isometric mid-thigh pull, IMTP

Introduction

Evaluation of strength imbalances in athletes has often been used to assess their physical ability. Indeed, strength imbalances have also been reported in well-trained athletes.2 There are a number of factors that could contribute to strength imbalance such as previous injury, repetition of sport specific movement, structural imbalance and dominance of hands and legs.3 Furthermore, authors advocated that such strength imbalance could limit performance and increase injury risk.4-8. Furthermore, kinematics of the lower extremities and horizontal ground reaction force (GRF) have been reported to be asymmetrical during both acceleration and maximum velocity sprinting.9-11. Therefore, information about strength imbalances in athletes is essential for the athletes, their coaches and therapists to assess the physical characteristics of performance and inform injury risk.

Strength imbalances of the lower extremity have been assessed using knee extension-flexion exercises with an open kinetic chain which is a movement without supporting body weight by distal end of extremity.12-14. Whereas, regarding the assessment of strength imbalance, it has been suggested that closed kinetic chain exercise (CKCE) - a movement supporting body weight by an arm or leg - would be preferable to open kinetic chain exercise. Athletic performance results from multi-joint force generation whilst supporting body weight by an arm or leg would be preferable to open kinetic chain exercise. Athlete's performance during sprint running. Some studies have examined strength imbalances through closed kinetic chain multi-joint exercises.10,11,15-17. Jones and Bampouras18 demonstrated the suitability of single leg jump exercises such as horizontal jumps, drop jumps and vertical jumps in order to detect strength asymmetry. Petschnig et al.19 stated that strength imbalances detected by single leg vertical jumps would be effective predictors of recovering strength and
function of injured legs of patients with anterior cruciate ligament (ACL) injury. Furthermore, the additional advantage of evaluating strength imbalances with such jump exercises is that they are feasible without using specific equipment and they don’t require much time or space to perform. However, Newton et al.\(^3\) implied that evaluation of strength imbalance using these jump exercises might not be accurate because strength imbalance detected by closed kinetic chain multi-joint exercises did not agree with those of knee extension with an open kinetic chain. This discrepancy in results may be due to dynamic exercises requiring greater intermuscular coordination compared to single joint exercises like knee extension-flexion exercises, which could influence strength imbalance for individual athletes. Therefore, it is suggested that when evaluating strength imbalances, closed kinetic chain multi-joint exercises are used to detect imbalance without the influence of technique.

Another problem when investigating strength imbalances is the lack of consensus in the definition of limb dominance. Often, the preferred leg used to kick a ball of strength - can be assessed without taking much time. Depending on the definition of a self-reported dominant leg\(^{12-14}\). Conversely, previous studies that have examined strength imbalances of well-trained athletes have defined limb dominance from force generation without using the definition of a self-reported dominance\(^3,10\). To our knowledge, it has not been clarified whether or not a self-reported leg is consistent with the dominant leg defined by maximal force generation. There is the possibility that a misunderstanding of the relationship between self-reported dominance and dominance associated with force generation leads coaches to design inappropriate training plans. In fact, Hoffman et al.\(^{13}\) revealed that a self-reported dominant leg does not always outperform a non-dominant leg in the ability to control the body balance during single leg stance. While, Östenberg et al.\(^{15}\) examined the consistency between a self-reported dominant leg definition and dominant leg based on force exerted during single leg vertical jumps. However, a single leg vertical jump may not be appropriate to define limb dominance due to the swing movement of the contralateral leg, which could contribute to jump height\(^{19}\). Thus, it is important to define the dominant leg of force generation with exercises that are not influenced by other factors.

Considering the aforementioned issues, a closed kinetic chain exercise involving an isometric contraction would be a suitable exercise to define the dominant leg of force exerted because the isometric exercise allows greater control over other factors that might influence the outcome. As the typical exercise of multi-joint closed kinetic chain pattern exercise with isometric contraction, the isometric mid-thigh pull (IMTP) has been widely used to evaluate strength characteristics of athletes and to predict various athletic performances such as sprint running, change of direction and jump performance\(^{17-20}\). In traditional assessment of strength using the one repetition maximum (1RM) method, much time is required to determine the maximum weight that an athlete can lift, and such exercise with very heavy weight might lead to injury for some athletes who are not well familiarized with strength training. On the other hand, the advantages of IMTP are that it can be performed with little risk of injury to athletes, and strength characteristics - such as maximum strength and explosive strength - can be assessed without taking much time. Furthermore, IMTP is also used to detect the strength imbalances of athletes\(^{21,22}\). In previous studies, two types of IMTP have been utilized for detecting strength imbalances; Bailey et al.\(^{29}\) attempted to reveal bilateral asymmetry by using IMTP in bilateral stance (IMTP\(_b\)). While, Dos’Santos et al.\(^{22}\) attempted to reveal unilateral asymmetry by using IMTP in unilateral stance (IMTP\(_u\)). These previous studies indicated the force generation during performance of IMTP was effective in evaluating strength imbalances. However, the relationship between imbalanced force generation and neuromuscular activity were not examined in those previous studies. In addition, we still don’t know about possible differences in strength imbalances detected by IMTP\(_b\) and IMTP\(_u\), since they were examined in separate studies previously.

Therefore, the present study was conducted to compare force generation as well as neuromuscular activities of lower extremities between dominant and non-dominant legs in IMTP\(_b\) and IMTP\(_u\). Thus, we aimed to examine whether a self-reported dominant leg was consistent with a dominant leg of force determined by using the IMTP tests. Additionally, this study was aimed at identifying the features of IMTP\(_b\) and IMTP\(_u\) in terms of detecting strength imbalance of athletes. The overall purpose of the present study was to scientifically determine how to interpret and analyze asymmetry of strength regarding the use of IMTP tests for coaches.

**Materials and Methods**

**Participants.** Fifteen male collegiate athletes (age, 20.60 ± 1.50 years; height, 1.74 ± 0.05 m; mass, 69.04 ± 4.23 kg) volunteered for this study. Participants 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.** Participants performed IMTP\(_b\) and IMTP\(_u\) exercises during the same testing session. The GRF and surface electromyography (sEMG) of the muscles in the lower extremities were simultaneously measured in IMTP\(_b\) and IMTP\(_u\). For sEMG, the neuromuscular activities of the gluteus maximus (G\(_{max}\)), gluteus medius (G\(_{med}\)), semitendinosus (ST), biceps femoris (BF), rectus femoris (RF), and vastus lateralis (VL) were assessed. All
participants practiced the IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni} exercises more than 48 hours prior to testing to remove the influence of fatigue.

**IMTP testing.** Both IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni} were implemented by standing with one foot on each of two force plates sized 0.6 × 0.6 m (Ex-Jumper, DKH, Tokyo, Japan), to collect the GRF of vertical component in a custom designed power lifting rack (Fig. 1). The vertical GRF collected during both IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni} was sampled at 1000 Hz on each leg. 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° before performing IMTP\textsubscript{Bi} by using a hand held goniometer\textsuperscript{23}. Moreover, instruction was provided for participants to keep the trunk in an upright position\textsuperscript{24}. For IMTP\textsubscript{Uni}, the knee and hip angles of the stance leg and trunk position were also standardized in the same manner as IMTP\textsubscript{Bi} to ensure the same body posture as for IMTP\textsubscript{Bi}. The knee angle of the unsupported leg during IMTP\textsubscript{Uni} was held at approximately 90°, and a swinging motion was prohibited\textsuperscript{25}. Additionally, all participants were instructed to keep the elbow straight, shoulder down and back straight during both IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni} to minimize the influence of trunk and arms. After general and specific warm-up, the participants performed IMTP\textsubscript{Bi}. After that, IMTP\textsubscript{Uni} was performed for the right and left legs in a randomized order. As a specific warm-up for IMTP, two practice attempts at 50% and 75% of the participant’s perceived maximum effort were performed before IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni}\textsuperscript{17}. For recovery from maximum force generation, a rest period of 2 minutes was provided between each trial\textsuperscript{17,22}. It was instructed to pull the bar as hard and fast as possible for four seconds, and all participants received verbal encouragement to exert their maximum effort during IMTP testing.

Concerning data analysis, for IMTP\textsubscript{Bi}, the total GRF of the right and left legs was used to determine the onset of the pull as the point when GRF exceeded 105% of the participant’s body weight\textsuperscript{17}. Peak vertical force (PF) in the four seconds of pulling was calculated as absolute GRF minus the participant’s body weight\textsuperscript{20}. For the IMTP\textsubscript{Uni} trials, the onset of pull and PF were determined based on the vertical GRF in the same manner as IMTP\textsubscript{Bi}. Testing attempts were performed three times for IMTP\textsubscript{Bi} and IMTP\textsubscript{Uni} on each leg, and the order of the right and left legs in IMTP\textsubscript{Uni} was randomized. The top two PF trials were selected based on three trials, and the PF of the selected trials were averaged for further analysis. The test-retest reliability for PF met the standard for reliability of the IMTP variables, which was intra-class correlation coefficient (ICC) > 0.70\textsuperscript{26}.

**sEMG.** Participant hair was shaved at the site of sEMG electrode placement, and the skin was also cleaned with alcohol before placing the electrode. The sEMG signals were recorded by 3.00 cm diameter electrodes with an inter-electrode distance of 0.9 cm (Nihon Kohden, Tokyo, Japan). A preamplifier was incorporated into each electrode and the signal was further amplified by using

---

![Fig. 1](image-url)  
**Fig. 1** A custom designed power rack for isometric mid-thigh pull testing using dual force plates.
an amplifier. The butterworth digital filter at 10 Hz was applied to sEMG data in order to eliminate data noise. All sEMG data was sampled at 1000 Hz. The electrodes were placed on both legs along the direction of the muscle fibers of each muscle. The placement of the sEMG electrodes on each muscle was determined in accordance with the SENIAM protocol, which is the global standard for collecting sEMG data. For neuromuscular activities of the lower extremity in both IMTPBi and IMTPUni, each sEMG was averaged based on the top two PF trials, as well as force generation. Neurromuscular activities for PF were averaged 100 ms before and after the point when PF appeared. In normalization, surface EMG during IMTPBi was normalized by using surface EMG during IMTPUni. Since surface EMG should be normalized by signals that are detected in the same posture and joint angles, IMTPUni was used as the referent control. Thus, by using that normalization, neuromuscular activities between legs in IMTPBi were compared in the present study.

**Definition of legs.** In the present study, two types of definitions were used. Firstly, legs were separated into dominant and non-dominant leg in accordance with the self-report, as well as previous studies. In this manner, the leg used to kick a ball preferentially was defined as a self-reported dominant leg. Secondly, dominance was defined as the leg that exerted the larger PF in IMTPBi or IMTPUni was defined separately as the dominant leg, while the leg that exerted the smaller force was defined as the non-dominant leg. Although some participants did not differentiate the dominant legs between IMTPBi and IMTPUni, in the present study, this inconsistency was not discussed in accordance with previous studies.

The imbalance index in force generation between dominant and non-dominant legs was calculated by the following formula: (dominant leg – non-dominant leg) / dominant leg *100, used in previous studies. The imbalance index was only used to compare the magnitude of asymmetry between dominant and non-dominant legs of force generation not in self-reported dominant and non-dominant legs. By comparing the imbalance index between IMTPBi and IMTPUni, the difference of magnitude of asymmetry was clarified.

**Statistical analysis.** Descriptive analyses that included mean, standard deviation (SD) and coefficient of variation were calculated. ICC was used for within-session test-re-test reliability of PF and sEMG. The paired t-test was used to determine the difference between dominant and non-dominant legs in PF and sEMG. The criterion for statistical significance was considered as p < 0.05. Cohen’s d-value effect size was calculated based on mean and SD to show practical significance, and was interpreted as trivial (< 0.19), small (0.20 - 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) in accordance with Hopkins. The paired t-test and ICC were performed using SPSS v22 software (IBM, New York, USA).

**Results**

The mean and SD of PF in self-reported dominant and non-dominant legs during IMTPBi and IMTPUni are shown in Table 1. Mean PF values were larger for a self-reported dominant leg than non-dominant leg in both of IMTPBi and IMTPUni, but there was no significant difference between limbs (IMTPBi: p = 0.922, d = 0.03, IMTPUni: p = 0.416, d = 0.15). Furthermore, it was also found that there was inconsistency between self-reported dominance and force generation dominance. Specifically, in five participants, a self-reported non-dominant leg exerted a larger PF than the dominant leg in IMTPBi. Similarly, in IMTPUni, there was disagreement between a self-reported dominant leg and dominant leg of force generation in seven of the fifteen participants. Neuromuscular activities of self-reported dominant and non-dominant legs during IMTPBi are shown in Table 2. There was no significant difference between limbs for neuromuscular activities in IMTPBi.

Table 3 includes PF values for IMTP trials and demonstrates that there were significant differences between dominant and non-dominant legs of force generation for IMTPBi and IMTPUni (IMTPBi: p < 0.05, d = 1.12; IMTPUni: p < 0.05, d = 0.56). Fig. 2 compares the imbalance index between IMTPBi and IMTPUni (IMTPBi: 23.28 ± 14.37 %, IMTPUni: 10.26 ± 8.09 %). The imbalance index of IMTPBi was found to be significantly larger than that of IMTPUni (p < 0.05, d = 1.12). Neuromuscular activities of all muscles in dominant and non-dominant legs of force generation during IMTPBi are shown in Table 4. In IMTPBi, the neuromuscular activity of only VL of the dominant leg was significantly larger than those of the non-dominant leg (VL: p < 0.05, d = 0.92).

**Discussion**

The purposes of the present study were (a) to determine whether a self-reported dominant leg was consistent with a dominant leg of force generation and (b) to identify the different features of IMTPBi and IMTPUni in detecting strength imbalance. In the PF of IMTPBi and IMTPUni, no significant differences were found between self-reported dominant and non-dominant legs. However, when comparing dominant and non-dominant legs that were defined in accordance with force generation, there were significant differences in the PF. Moreover, the PF imbalance between legs during IMTPBi was significantly higher than IMTPUni. Therefore, neuromuscular activities were compared between legs during IMTPBi by using IMTPUni as a referent control to normalize sEMG.

The absence of strength imbalances between self-reported dominant and non-dominant legs in force gen-
Asymmetry of force generation and neuromuscular activity

Table 1. Comparison between self-reported dominant and non-dominant legs in PF.

<table>
<thead>
<tr>
<th></th>
<th>Dominant (N)</th>
<th>Nondominant (N)</th>
<th>Paired t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>p-value</td>
</tr>
<tr>
<td>IMTPBi</td>
<td>1015.26 ± 257.74</td>
<td>1006.28 ± 298.72</td>
<td>0.922</td>
</tr>
<tr>
<td>IMTPUni</td>
<td>1613.15 ± 283.11</td>
<td>1567.57 ± 336.62</td>
<td>0.416</td>
</tr>
</tbody>
</table>

Table 2. Comparison of neuromuscular activities between self-reported dominant and non-dominant legs in IMTPBi.

<table>
<thead>
<tr>
<th></th>
<th>Dominant (%)</th>
<th>Nondominant (%)</th>
<th>Paired t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>p-value</td>
</tr>
<tr>
<td>Gmax</td>
<td>54.31 ± 21.46</td>
<td>58.44 ± 28.34</td>
<td>0.625</td>
</tr>
<tr>
<td>Gmed</td>
<td>57.33 ± 35.45</td>
<td>53.58 ± 25.91</td>
<td>0.644</td>
</tr>
<tr>
<td>ST</td>
<td>82.61 ± 37.15</td>
<td>90.96 ± 64.80</td>
<td>0.516</td>
</tr>
<tr>
<td>BF</td>
<td>62.45 ± 29.95</td>
<td>60.23 ± 35.79</td>
<td>0.827</td>
</tr>
<tr>
<td>RF</td>
<td>62.09 ± 22.28</td>
<td>63.73 ± 21.65</td>
<td>0.867</td>
</tr>
<tr>
<td>VL</td>
<td>66.89 ± 24.41</td>
<td>57.68 ± 15.54</td>
<td>0.263</td>
</tr>
</tbody>
</table>

Table 3. Comparison between dominant and non-dominant legs of force generation in PF.

<table>
<thead>
<tr>
<th></th>
<th>Dominant (N)</th>
<th>Nondominant (N)</th>
<th>Paired t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>P-value</td>
</tr>
<tr>
<td>IMTPBi</td>
<td>1146.00 ± 242.84</td>
<td>875.54 ± 239.89</td>
<td>†</td>
</tr>
<tr>
<td>IMTPUni</td>
<td>1674.13 ± 286.00</td>
<td>1506.60 ± 312.64</td>
<td>†</td>
</tr>
</tbody>
</table>

†: significant difference (p < 0.05)

Fig. 2 Comparison of imbalance index between IMTPBi and IMTPUni.

†: significant difference (p < 0.05)
cause of a similar movement between legs during sprinting. Such sport-specific movements and requirements could influence the results of strength imbalance in the present study. However, in a previous study, it was also demonstrated that a self-reported dominant leg, which was defined as the preferential leg to kick a ball, has not always been superior in the ability to control body balance\(^\text{10}\). The findings support the inconsistency between self-reported dominance and dominance associated with force generation. On the other hand, Östenberg et al.\(^\text{15}\) also defined a self-reported dominant leg by using the criteria of the leg of kicking a ball. In their study, they also compared the performance of single-leg jumps - such as one leg hop and triple jump with one leg - between self-reported dominant and non-dominant legs. As a result of their examination, no difference was found between legs. However, it is important to note that single leg jump performance is influenced by, not only the ability to generate force, but also the technique and coordination of movement since the swing movement of the unsupported leg could contribute to increased vertical GRF\(^\text{10}\). Therefore, like the IMTP, the factors of a given technique should be standardized to define the dominant leg accurately with as little influence of other factors as possible. Furthermore, it has been previously reported that IMTP variables such as force generation at the point of 100 milliseconds (ms) after onset of pulling and peak force in IMTP are positively correlated with sprint and change of direction performance\(^\text{17-20}\). Thus, the dominance of force generation that was defined using IMTP seems to be connected to the dominance in those dynamic movements. This link suggests that IMTP may be extremity effective as an evaluation tool to quantify strength imbalance that may lead to asymmetry identified in dynamic movement\(^\text{5}\).

When comparing dominant and non-dominant legs of force generation, the results of the present study revealed that IMTP\(_{\text{Bi}}\) detected a larger magnitude of strength imbalance compared to IMTP\(_{\text{Uni}}\). In the PF, between dominant and non-dominant legs of force generation, significant differences were found in both IMTP\(_{\text{Bi}}\) and IMTP\(_{\text{Uni}}\); however, the imbalance index of IMTP\(_{\text{Bi}}\) was significantly larger than that of IMTP\(_{\text{Uni}}\). One possible cause of the difference in detected strength imbalance between the bilateral and unilateral stance might be associated with the unconscious selection of either leg during IMTP\(_{\text{Bi}}\). During IMTP\(_{\text{Bi}}\), participants may subconsciously select their preferred leg to exert greater force because they could choose using either leg in the bilateral stance. In other words, the preferred leg would attempt to compensate for non-preferred leg during maximal force exertion in the IMTP\(_{\text{Bi}}\). Newton et al.\(^\text{3}\) reported similar findings that imbalanced force generation between limbs was found during bilateral squat exercises, and mentioned that the asymmetry of athletes through bilateral stance exercises can be effectively evaluated. In contrast, during IMTP\(_{\text{Uni}}\), participants were forced to use one leg during each trial, as the other leg was not in contact with the ground, which may have allowed participants to generate more force with their ‘non-preferential’ leg when it was isolated.

Regarding the comparison of neuromuscular activities between dominant and non-dominant legs of force generation in IMTP\(_{\text{Bi}}\), Table 4 presents the comparison of neuromuscular activities between dominant and non-dominant legs of force generation in IMTP\(_{\text{Bi}}\). The table includes the mean ± standard deviation (SD) for the dominant and non-dominant legs, paired t-test p-value, and Cohens’s d effect size. The table shows that the dominant leg demonstrated significantly higher neuromuscular activity in the VL compared to the non-dominant leg. The reason why a significant difference was found in the VL could be because the VL is classified as a mono-articular muscle and mainly contributes to knee extension torque\(^\text{29}\). So, although there was no significance in G\(_{\text{max}}\), which works as a hip extensor, the mean value of the dominant leg was also much higher than that of the non-dominant leg. Since the IMTP
is an exercise to evaluate the strength of the lower extremity, knee and hip joint force would greatly influence total GRF. Based on results in the present study, imbalanced neuromuscular activation around the knee joint would be the key feature of asymmetry of strength. It is impossible to identify an exact mechanism that causes imbalanced neuromuscular activation of the VL between legs because only the surface EMG was recorded and analyzed in the present study. Nevertheless, it could be speculated that inter-hemispheric inhibition (IHI) in the motor cortex might be a possible mechanism to explain the imbalanced neuromuscular activation of the VL between legs. According to Duque et al.30), IHI is a mechanism that leads to increased neuromuscular activity of a dominant hand as well as inhibited neuromuscular activity of a non-dominant hand during functional hand movement. In the previous study, it was revealed that inhibition on one side of the motor cortex led to the discrepancy between dominant and non-dominant hand movements. Therefore, based on the results of the present study, only the VL of the non-dominant leg of force generation may have been inhibited during the isometric activities. However, surface EMG data is not enough to discuss central nervous system (CNS) behavior as it was described above. Therefore, for a more detailed discussion of CNS behavior in terms of imbalanced neuromuscular activation between legs, it is required to analyze the coordination among the muscles and physiological responses of motor neuron pool such as motor unit firing properties and reflex modulation, as well as surface EMG in future research.

Based on the results of the imbalanced neuromuscular activities of the VL between dominant and non-dominant legs of force generation in IMTPBi, it was identified that the strength imbalance detected by IMTPBi would be influenced by imbalanced neuromuscular activation. Furthermore, the strength imbalance evaluated by PF was much higher in IMTPBi compared to IMTP Uni due to unconscious selection. The difference in IMTPBi and IMTPUni in terms of strength imbalance can be selectively applied according to practical situations. For instance, Konishi et al.31) argued that ACL reconstruction influences the γ-loop of the injured leg adversely, and this dysfunction of the CNS would be a long-term limiting factor of performance. In this situation, IMTPBi would be an effective tool for evaluating strength imbalance including the effect of neuromuscular activation for some patients. On the other hand, IMTPUni allows a comparison of pure muscle strength between limbs, as well as the exercises implemented previously such as knee extension and flexion exercises. Asymmetry reported during dynamic movement3) identified that sprint asymmetry varied depending on the individual, and that the relationship between strength imbalance and biomechanical asymmetry was not consistent across different athletes or functions of performance. Based on the results of this previous study, evaluating strength imbalance is a complex task that depends on a number of participant-specific factors, which would be difficult to perform within a single exercise. Therefore, it is recommended that, whilst movements such as IMTP may be very beneficial in identifying overall strength imbalance, coaches should also consider evaluating strength imbalances individually through various types of exercises to identify the cause of any overall imbalance. Accordingly, injury risk could be reduced and performance improved by eliminating strength imbalance.

A limitation of the present study was that the self-reported dominant leg was decided based on which leg was preferred in kicking a ball. Thus, there was the possibility that participants did not understand the physiological and biomechanical capacity of each leg. Such a misunderstanding could lead to selecting the incorrect dominant leg. Another limitation was that the study did not examine the neuromuscular activities of the trunk and upper extremity. Although the posture of participants was standardized, an unconscious inclination of the body might cause imbalanced GRF. It is speculated that muscles of the trunk and upper extremity, such as the trapezius and elector spinae, could also produce force during IMTP and compensate for strength imbalance in the lower extremity. The elector spinae, especially, could contribute to producing GRF by hip extension movement, so that imbalanced activation of the elector spinae could influence the asymmetry of GRF. Therefore, future work in this area could add to the findings of this study by examining strength imbalances of the trunk and upper extremity during IMTP.

In conclusion, we revealed that a self-reported dominant leg was not consistent with a dominant leg of force generation. Furthermore, between dominant and non-dominant legs of force generation, it was also demonstrated that the asymmetry of PF in IMTPBi was larger than IMTPUni, and the imbalanced PF of IMTPBi was related to a discrepancy in neuromuscular activation of the VL. These results suggest the possibility that the strength imbalances detected by IMTPBi and IMTPUni could have a different meaning. Therefore, depending on the situation, IMTPBi and IMTPUni should be distinguished in evaluating the strength asymmetry of athletes properly.

**Conflict of Interests**

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

**References**

3) Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK,


