The Effect of Fatigue on Asymmetry Between Lower Limbs in Functional Performances in Elite Child Taekwondo Athletes

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Abstract

**Background:** Inter-limb asymmetry above a certain threshold in functional performance indicates increased injury risk in sports. Fatigue has been found to increase bilateral asymmetry in lower-limb jumping performance among high-school and adult athletes, whereas this impact has not been examined for child athletes.

**Methods:** Performance of single-leg jumps, Star Excursion Balance Test (SEBT), and muscle (hamstring and gastrocnemius) flexibility were measured for 13 elite male child Taekwondo athletes (aged 9.85 ± 0.80 years) at both the rested and fatigued states to examine the inter-limb asymmetry. A two-way repeated measures ANOVA was conducted to examine for difference for each test and the interaction between limb (dominant, non-dominant leg) and state (rested, fatigued state). Paired t test or Wilcoxon Signed-Rank test was used to compare the asymmetry magnitude at the rested vs. fatigued state for each test, and the variation in performance post fatigue in the dominant vs. non-dominant leg when appropriate.

**Results:** The inter-limb asymmetry in triple-hop distance significantly \((p = 0.046)\) increased with fatigue, whereas the asymmetry significantly \((p = 0.004)\) decreased with fatigue in anterior (ANT) reach distance in SEBT. A significant \((p = 0.027)\) limb by state interaction was shown for posterolateral (PL) reach distance in SEBT, wherein a significant \((p = 0.005)\) bilateral difference was only shown at the rested state. The PL reach distance showed a significantly greater decrease \((p = 0.028)\) post fatigue when using the dominant leg for support compared to using the non-dominant leg.

**Conclusion:** Fatigue significantly impacts inter-limb asymmetry in jump performances and dynamic balance for child athletes, while the variation in inter-limb asymmetry post fatigue may be different across tests. For the purpose of injury prevention, practitioners should consider assessing the inter-limb asymmetry for children at both the rested and fatigued state, and be mindful of the fatigue response of each leg in functional tests.

**Introduction**

Inter-limb asymmetry (or bilateral difference, bilateral asymmetry) is defined as differences in the function or performance between the dominant and non-dominant limb [1]. Inter-limb asymmetry may emerge from long-term training in the same sport [2, 3]. There is a growing interest on the topic of inter-limb asymmetry because of its influence on risk for sport injury. The inter-limb asymmetry may potentially place the lower extremities of both sides at an heightened risk of sport injury [4]. The strong leg may sustain overloading of muscle-tendon components because of increased dependence and prolonged exposure to high force in sport activities, while it may be difficult for the weak leg to manage even average stress and force [4]. The bilateral asymmetry in lower-limb strength and power [5], dynamic balance [6, 7], and muscle flexibility [5] have been associated with increased injury risk in high-school and collegiate athletes.
Current literature have suggested the importance of investigating the impact of fatigue on inter-limb asymmetry, due to the potential for asymmetry becoming more prominent with fatigue [8]. The increased inter-limb asymmetry may play a role in the heightened injury risks under the fatigued state [9]. A number of studies have focused on the running biomechanics with inconsistent findings. Radzak et al. [10] reported that fatigue amplified the inter-limb asymmetry in knee internal rotation and knee stiffness (increased by 14% and 5.3%, respectively) in healthy adults’ running (4 m/s) movement, whereas the inter-limb asymmetry in vertical stiffness and loading rate decreased post fatigue. However, most of the previous studies revealed that there was no impact of fatigue on kinematics and kinetics in running movement [11-14].

In contrast, there is a paucity of research examining the acute impact of fatigue on inter-limb asymmetry in functional testing performance. The unilateral jump testing has been widely used to assess the inter-limb asymmetry in lower-limb power as the single-leg jumping movement is common in sports and the assessment is time-efficient [9]. Previous findings showed that the inter-limb asymmetry in single-leg countermovement jump (CMJ) performance increased post fatigue among adolescents and adults [9, 15, 16]. In addition to the unilateral jump performance, the Star Excursion Balance Test (SEBT) and its modified version (Y Balance Test) have been widely used to examine inter-limb asymmetry in dynamic balance and neuromuscular control. However, to the best of our knowledge, the acute effect of fatigue on inter-limb asymmetry in SEBT or Y Balance Test performance has not been reported. Also, the influence of fatigue on inter-limb asymmetry in muscle flexibility which has been reported as a risk factor for sport injury [5] is not clear.

Current literature has mostly examined athletes in high-school and adulthood years, whereas there is a paucity of research in this field focused on child athletes. Compared to adult athletes, athletes in childhood-age are more vulnerable to injuries because the immature cartilage and muscles are more susceptible to injuries in sports [17, 18]. Acute and overuse injuries in the growth cartilage may cause permanent damage to bone growth if they are not treated well [18]. Radelet et al. [18] have reported that the injury rate ranged from 1.0 to 2.3 per 100 athlete exposures in 7-13 year old children in community sports. Examining the inter-limb asymmetry in functional performances and the impact of fatigue on this asymmetry is important for the purpose of injury prevention among child athletes, due to the association between inter-limb asymmetry and increased injury risk [5-7]. Therefore, the purpose of the present investigation was to examine the acute impact of fatigue on inter-limb asymmetry in lower-limb power, dynamic balance, and muscle flexibility among child athletes. Generating these findings will contribute to understanding the association between fatigue, inter-limb asymmetry, and injury.

**Methods**

**Participants**

A total of 13 elite male Taekwondo athletes (height = 144.31 ± 7.81 cm, body mass = 37.58 ± 9.20 kg, age = 9.85 ± 0.80 years, training years = 3.31 ± 0.86 years) between 9 and 11 years of age were recruited. All
participants had accepted single-sport training (specialized at Taekwondo) and won medals in national level or provincial tournaments. All participants had at least one year of training experience and maintained regular training in the preceding 12 months before participation.

Assessments of bilateral asymmetry

Lower-limb power

Lower-limb power tests included the single-leg countermovement jump (CMJ), hop, and triple-hop tests. Unilateral jump tests have been shown to be valid and reliable (Intra-class correlation coefficient [ICC] = 0.81-0.99) for assessing the inter-limb asymmetry of leg power [19].

The goal of the single-leg CMJ test was to obtain the maximum jump height of each leg after performing a single-leg countermovement. Participants stood in an upright position with feet positioned shoulder width apart. The hands were placed on hips during the entire movement to reduce the impact of arm movement [20]. To start the test, the participant lifted one leg to a self-selected position, and then performed a countermovement followed by a vertical jump. The jump was recorded with an iPhone 6s (Apple, Inc., USA) at 240 Hz. The jump height (in cm) was calculated based on the flight time of the jump by identifying the take-off and landing frames using the “My Jump” iPhone application, which has been reported a valid and reliable method [21]. Three valid trials were required for each leg. The jump height (in cm) for each trial was recorded. The average jump height of the three trials of each leg was used for analysis.

The goal of the single-leg hop and triple-hop test was to obtain the maximum horizontal distance of a hop and three consecutive hops, respectively. Participants started with a unilateral standing position and toes of the supporting leg behind the starting line. For the one hop test, participants were instructed to perform a forward hop as far as possible and land firmly with the same leg. Failure to perform a firm landing was viewed as an invalid trial. The hop distance (in cm) from the starting line to the participant’s landing heel was measured and recorded. For the triple-hop test, participants were instructed to perform three consecutive forward hops as far as possible using the same leg, with the intention of reducing the floor contact time of the first two landings as much as possible. The landing of the last hop had to be firm. Failure to perform a firm landing at the last hop was viewed as an invalid trial. The total hop distance (in cm) from the starting line to the participant’s final landing heel was measured and recorded. Three valid trials were required for each leg in each test. The average distance (in cm) of the three trials of each leg in each test was used for analysis.

Dynamic Balance

Dynamic balance was measured using the Star Excursion Balance Test (SEBT) which is a valid and reliable (ICC = 0.78-0.96) [22] test developed by Gray [23]. The sketch of the SEBT is presented in Figure 1. The goal of this test was to obtain the maximum reach distance along three directions (Anterior [ANT], Posteromedial [PM], and Posterolateral [PL]) using the contralateral leg while maintaining a unilateral
stance with solid foundation [24]. While standing with a single leg at the convergence of reach direction lines, participants were required to reach as far as possible with the other leg along each of the three directions (in the order of ANT, PM, and PL direction), lightly touching each line using the most distal part of the reaching foot without disrupting the established balance during the entire movement. The point where the most distal part of the foot reached was marked with erasable ink on each direction line. Each participant performed three trials (each trial with three directions) using each leg. Participants took this test barefoot to eliminate the effects of shoes on balance and stability. The trial was viewed as invalid when participants failed to maintain the unilateral stance, moved or lifted the standing foot from the convergence of lines, or failed to return the reaching foot to the original position [6]. The greatest reach distance (in cm) from the convergence of lines to the point where the most distal part of the foot reached in three trials for each direction of each leg was measured and used for analysis [6].

Hamstring and gastrocnemius flexibility

Hamstring and gastrocnemius flexibility was measured using a goniometer which has been identified with high validity and reliability (ICC = 0.98-0.99) [25]. Specific protocols for measurements are reported elsewhere [26]. The goal of this test was to obtain the maximum range of motion of hip and ankle joint in a specific position reflecting the flexibility of the hamstring and gastrocnemius. The flexibility of the hamstring was measured with the participant in a supine position on a table. The participant lifted one of the legs straightening with the help of an examiner and the angle (º) of the hip flexion was measured. The axis of the goniometer was placed at the great trochanter. The stationary arm of the goniometer was placed horizontally at the table, and the moving arm was placed pointing to the lateral epicondyle of the femur. The flexibility of the gastrocnemius was measured with the participant pushing hands on a wall fully extending the arms, and the tested leg behind the opposite leg. The participant fully extended the knee of the tested leg, and then maximally flexed the ankle of the tested leg while maintaining the sole on the floor. The angle (º) of the dorsiflexion at the ankle was measured. The stationary arm of the goniometer was placed horizontally to the floor, and the moving arm was placed pointing to the most distal part of the fibula. The angles (º) measured using the goniometer were used for analysis.

Fatigue induction

The fatigue protocol was modified from previous research [27, 28]. First, the participant was asked to perform a broad jump (three trials) to obtain the maximum horizontal distance (in cm) achieved at a rested state. The participant then performed two sets of 30-second consecutive double chop kicks on the punching bag at the maximum frequency, with a break of 30 seconds between sets. After completing the kicks, participants received a 30-second rest, followed by performing consecutive frog jumps until exhaustion. The criteria for fatigue was reached when the participant failed to reach 90% of the maximum broad jump distance at the rested state in three consecutive trials [27, 29].

Procedures
Participants finished all assessments in one visit. First, anthropometric measurements including body height (cm), leg length (cm), and body weight (kg) were taken. Leg length was measured from the anterior superior iliac spine to the most distal aspect of the medial malleolus with participants lying supine on a table. Limb dominance was examined by letting the participant kick a soccer ball, and the limb which the participant preferred for the ball kicking was defined as the dominant leg. In the session, participants then completed stretching and a five-minute jog to warm-up. Participants were then provided with test instructions and received time to practice until they were familiar with each assessment, which included tests measuring lower-limb power (single-leg CMJ, hop, and triple hop), dynamic balance (SEBT), and muscle flexibility (hamstrings and gastrocnemius). Following test familiarization, participants received a rest interval of 5 minutes.

Testing followed a three-phase approach: 1) testing at a rested state, 2) fatigue induction, and 3) testing at a fatigued state. Testing at a rested state was conducted in the following order: single-leg CMJ, hop, triple hop, SEBT, and flexibility of the hamstring and gastrocnemius, with a one-minute rest interval between each assessment. At the end of the first phase, participants received a 5-minute rest period, followed by the fatigue induction phase until fatigue criteria was reached. The third phase, testing at a fatigued state, was conducted exactly the same as testing at the rested state except that participants were asked to run continuously between trials with no rest provided between assessments. The starting leg was randomly selected to reduce the effect of order.

Data Analysis

Dependent variables included the single-leg CMJ height, hop distance, triple-hop distance, the reach distance (normalized to leg length) in each direction (ANT, PM, PL, and the composite score of the three directions [COM]) in SEBT, the angles measured in hamstring and gastrocnemius flexibility tests, the inter-limb asymmetry in performance at the rested and fatigued state for each test, and the variation in performance from the rested to fatigued state (fatigue rate) in each test for each leg. The mean of each dependent variable in lower-limb power tests (single-leg CMJ, hop, and triple hop) over the three trials was calculated for each participant. The reach distance in SEBT was normalized to leg length (leg length %), and the COM reach distance was calculated by averaging the reach distance of the three directions for each leg. The magnitude of inter-limb asymmetry for each test was quantified using an equation modified from previous studies [30, 31]: Asymmetry Index = (Stronger Limb – Weaker limb) \* 2 / (Stronger Limb + Weaker limb) \* 100%. The variation in performance from the rested to fatigued state of each leg was calculated as a percentage for each test: (Rested – Fatigued) \* 2 / (Rested + Fatigued) \* 100%.

Statistical Analysis

Descriptive data are shown as mean ± standard deviation (SD). Normal distribution and homoscedasticity assumption of the data were examined using the Kolmogorov-Smirnov and Levene's tests, respectively. A two-way repeated measures ANOVA was conducted to examine for difference for each test, and the interaction between limb (dominant, non-dominant leg) and state (rested, fatigued state). Where significant differences were found between limbs or states, paired t tests were performed.
To compare the inter-limb asymmetry between the rested and fatigued state in jump performance (unilateral CMJ, hop, and triple hop) and muscle flexibility (hamstring and gastrocnemius), a non-parametric test (Wilcoxon Signed-Rank test) was conducted as the data distribution was not normal. To compare the inter-limb asymmetry (as a percentage) between the rested and fatigued state in SEBT performance (ANT, PM, PL, and COM reach distance), paired $t$ tests were performed. The variation in performance from the rested to the fatigued state (fatigue rate) was compared between the dominant and non-dominant leg using a paired $t$ test for each test. Effect size (ES) was reported using Cohen’s $d$ for results in $t$ tests [32], and using the correlation coefficient for results in Wilcoxon Signed-Rank tests ($r = Z/\sqrt{n}$) [33]. Statistical significance was set a priori at $p < 0.05$. All data analysis was conducted using SPSS 23.

**Results**

**Lower-limb power**

Descriptive statistics for lower-limb power tests are presented in Table 1. There was a significant main effect of state for single-leg CMJ height ($F_{(1,12)} = 57.880, p = 0.000, h^2 = 0.828$), hop distance ($F_{(1,12)} = 87.557, p = 0.000, h^2 = 0.879$), and triple-hop distance ($F_{(1,12)} = 47.667, p = 0.000, h^2 = 0.799$). For each leg, participants showed significantly better performance at the rested state compared to that at the fatigued state ($p < 0.05$, ES $\geq 1.148$). The inter-limb asymmetry in triple-hop distance significantly increased at the fatigued state compared to that at the rested state ($Z = -1.992, p = 0.046$, ES $= 0.552$, Table 4).

**Dynamic balance**

Descriptive statistics for the SEBT are presented in Table 2. There was a significant main effect of state for ANT ($F_{(1,12)} = 8.113, p = 0.015, h^2 = 0.403$), PM ($F_{(1,12)} = 8.850, p = 0.012, h^2 = 0.424$), and COM ($F_{(1,12)} = 4.997, p = 0.045, h^2 = 0.294$) reach distance. A significant ($F_{(1,12)} = 6.312, p = 0.027, h^2 = 0.345$) limb by state interaction was shown for the PL direction: the reach distance at the rested state was significantly ($p = 0.005$, ES $= 0.938$) greater when establishing the unilateral stance using the dominant leg compared with using the non-dominant leg, while no significant ($p > 0.05$) difference was shown between the two sides at the fatigued state. The PL reach distance showed a significantly ($p = 0.028$, ES $= 0.695$) greater decrease, and the COM reach distance showed a tendency ($p = 0.056$) of greater decrease post fatigue when establishing the unilateral stance using the dominant leg compared to using the non-dominant leg. Results of paired $t$ tests showed that PM reach distance at the rested state was significantly greater ($p = 0.023$, ES $= 0.722$) than that at the fatigued state when establishing the unilateral stance using the dominant leg, whereas there was no significant difference ($p > 0.05$) between states when using the non-dominant leg. The inter-limb asymmetry in ANT reach distance significantly decreased at the fatigued state compared to that at the rested state ($p = 0.004$, ES $= 0.993$, Table 4).
Descriptive statistics for the muscle flexibility tests are presented in Table 3. No significant difference was found.

Discussion

Lower-limb power

A 15% inter-limb asymmetry in lower-limb power has been widely used for injury prediction, while it should be noted that there is a lack of prospective studies examining this relationship. Knapik et al. [5] reported that female college athletes with more than 15% inter-limb asymmetry in isometric knee flexor strength sustained more injuries at lower extremities, but the equation for asymmetry calculation was not presented. The previously reported cut-off value (15%) for predicting injury should be used with caution in practical application as there are various equations for calculating the inter-limb asymmetry and different equations may lead to different solutions. In addition, previous studies on the association between lower-limb power and injury risk mainly used isokinetic and isometric tests [5, 34, 35]. However, the functional jumping tests are recommended to assess the inter-limb asymmetry in leg power as the required stretch-shortening cycle and high-rate force production in these tests better reflect the characteristics of muscle actions in most of the sport activities [20].

We have reported inter-limb asymmetry in single-leg jump performances among child fencing and Taekwondo athletes (9-11 years old) in our previous study [36]. In the present study, no significant difference was found between limbs at the rested or fatigued state for performance in each jumping test based on group means. However, by calculating the inter-limb asymmetry for each participant, we found that the asymmetry magnitude of the participants was 8.20%, 6.64%, and 5.78% at the rested state, and 12.76%, 9.59%, and 9.69% at the fatigued state for the unilateral CMJ height, hop distance, and triple-hop distance, respectively. This finding implies the importance of assessing and quantifying the inter-limb asymmetry in unilateral jump performance on an individual basis. In fact, the inter-limb asymmetry has been shown with a variable nature as the SD was usually close to even higher than the mean [9], which supports the individual approach when taking inter-limb asymmetry as a measurement in practical application. The asymmetry magnitude in the present study was similar with those reported in previous research using the same method of calculation to quantify asymmetry: A 9.9 to 16.8% inter-limb asymmetry in peak force and power in bilateral CMJ was reported in 95% of the collegiate athletes [37], and a 6.3% inter-limb asymmetry in running single-leg jump height was reported in collegiate male basketball athletes [30]. Age-appropriate comparison in asymmetry magnitude is not available due to the paucity of research focused on children.

Regarding the acute effect of fatigue on lower-limb power, our results showed a main effect of state (rested vs. fatigued state) for leg power (single-leg CMJ height, hop distance, and triple-hop distance). The jump performance decreased post fatigue in both legs in all three tests, indicating that our protocol was appropriate to induce fatigue. By comparing the magnitude of inter-limb asymmetry between the
rested and fatigued state for each test, we found that the asymmetry increased post fatigue in triple-hop distance. Most of previous studies have reported similar findings: the inter-limb asymmetry in unilateral CMJ height increased post fatigue among active male adults (aged 28.9 ± 5.1 years) [9] and elite adolescent male soccer athletes (aged 17.6 ± 0.5 years) [15]; the inter-limb asymmetry in peak force, peak power, and mean power during the unilateral CMJ increased post fatigue among male Judo athletes (aged 22.5 ± 3.6 years) [16]. Collectively, these findings indicate that fatigue amplifies the inter-limb asymmetry in leg power, suggesting the necessity of assessing the inter-limb asymmetry at both the non-fatigued and fatigued state. However, based on our results, the conclusion remains elusive regarding the mechanism of the increased asymmetry post fatigue in triple-hop distance as no significant difference in fatigue rate (the variation in performance from rested to fatigued state) was found between legs. Jacques et al. [14] reported that the soleus activation amplitude reduced with fatigue in the dominant leg while not in non-dominant leg when examining the muscle activities using electromyography (EMG) during the running movement, suggesting a higher fatigue rate in the dominant leg. More studies are needed to compare the fatigue rate between limbs when examining the acute impact of fatigue on inter-limb asymmetry in leg power as direct evidence still lacking in current literature. Figuring out this problem may help the athletic trainers developing fatigue-resistant programme based on the fatigue response of each leg to improve sport performance and injury prevention for athletes. Furthermore, due to the lack of research focused on child athletes, more studies are warranted to examine how fatigue influences inter-limb asymmetry in leg power among child athletes.

SEBT performances

The inter-limb asymmetry in SEBT performance indicates a compromised ability of neuromuscular control when establishing a unilateral stance using the poor-performance side, which may increase the injury risk [38]. An inter-limb asymmetry greater than 4 cm in ANT reach distance indicated increased injury risk among high-school [6] and collegiate athletes [7]. However, it has been suggested that the reach distance should be normalized to leg length in order to accurately compare the performances between participants [39]. We have reported an inter-limb asymmetry ranged from 8.92 to 13.98% in PL reach distance (normalized to leg length) in SEBT among 9-11 year old male and female fencers and Taekwondo athletes in our previous research [36]. The present study demonstrated similar findings: the 9-11 year old male Taekwondo athletes showed a significant bilateral difference (9.97% asymmetry) in PL reach distance in SEBT at the rested state. Future research needs to examine the association between injury risk and inter-limb asymmetry in SEBT among child athletes, due to the lack of research focused on children.

Fatigue has been found to decrease reach distances in SEBT [40], whereas there is a lack of research designed to examine the acute impact of fatigue on inter-limb asymmetry in SEBT performance. The present study showed a significant interaction between limb (dominant vs. non-dominant) and state (rested vs. fatigued) for PL reach distance, wherein the significant bilateral difference was only shown at the rested state, implying that the fatigue rate might differ between the dominant and non-dominant leg. The greater decrement in PL reach distance, and a tendency of greater decrement in COM reach distance...
post fatigue when using the dominant vs. the non-dominant leg for support indicated that the SEBT performance decreased more when using the dominant leg for support, implying a reduced ability of neuromuscular control at the fatigued state when establishing a unilateral stance using the dominant leg. Furthermore, the PM reach distance significantly decreased post fatigue only when using the dominant leg for support, which also supported this view. Previous findings have indicated that the reach distances in SEBT were associated with the kinematics [41] and kinetics [42, 43] of the supporting leg. Therefore, the greater decrement of reach distance post fatigue when using the dominant leg for support may indicate a higher fatigue rate in the dominant leg. However, it should be noted that the SEBT challenges comprehensive physiological properties including strength, flexibility, proprioception, and balance [44], thereby the mechanism of the decreased reach distance in SEBT could be complex. We suggest future research examine the activity level in lower-limb muscles using EMG for the SEBT, and further explore which leg fatigues more by comparing the variation in muscle-activity levels caused by fatigue when using the dominant vs. non-dominant leg for support, since previous research using EMG for SEBT only focused on the dominant leg. This will help generating a better understanding for the influence of fatigue on inter-limb asymmetry in SEBT performance.

By quantifying the inter-limb asymmetry, we found that the asymmetry in ANT reach distance significantly decreased post fatigue, which is conflicting with the results in triple-hop tests wherein an increment in asymmetry was shown. Whilst challenging to explain, it must be acknowledged that the kinetic and kinematic mechanism is different between the jump tests and SEBT as the latter challenges more comprehensive abilities [44], thereby it may not be strange that the variation in inter-limb asymmetry caused by fatigue is different in direction between the two tests. Additionally, although we concluded that the fatigue rate might be greater in the dominant leg, no significant difference was found between legs in the decrease in ANT reach distance post fatigue and the means were close (4.40% vs. 4.61%), and thus the mechanism of the decreased asymmetry in ANT reach distance is unclear. Nevertheless, our findings indicate that the unilateral jump tests and SEBT should not be used interchangeably when assessing the influence of fatigue on inter-limb asymmetry. Another finding of the present study is that the variations in inter-limb asymmetry post fatigue were inconsistent across the reach directions in SEBT. The muscle activation and kinematic strategy have been reported substantially different across the reach directions in SEBT [45], which may explain the inconsistent results between reach directions.

An interesting result is that the PL reach distance increased by 2.17% post fatigue in the non-dominant leg. Similar results were reported by Armstrong et al. [41] when examining the effect of fatigue on SEBT performance among university dancers. According to the authors, the increased reach distance might be related to the distinct characteristics of the dance sport as the dancers may have distinct and variable kinematic strategies to maintain or even facilitate the SEBT performance under the fatigued condition [41]. In the present study, although the PL reach distance increased with fatigue (2.17%) in the non-dominant leg, this data should be used with caution in practice, due to the SD (8.04%) was much higher than the mean. Furthermore, this result reflects the variable nature of the inter-limb asymmetry, suggesting the importance of assessment on an individual basis when taking the inter-limb asymmetry in SEBT performance as a measurement in practical application.
Muscle flexibility

Poor flexibility of hamstring and gastrocnemius muscles has been associated with increased risks of lower-limb injuries [26, 46, 47]. Few research from current literature is available on the association between inter-limb asymmetry in muscle flexibility and injury risk. Knapik et al. [5] have reported that female collegiate athletes with a 15% or more bilateral asymmetry in hip extensor sustained more lower-limb injuries. Although this relationship has not been examined on children, practitioners may need to monitor the inter-limb asymmetry in muscle flexibility for child athletes to prevent its potential impact on injury risk. In the present study, the inter-limb asymmetry ranged from 7.09 to 11.33% in hamstring and gastrocnemius muscles at the rested and fatigued state. Regarding the impact of fatigue on inter-limb asymmetry in muscle flexibility, there is a paucity of research available in current literature. Our results showed that there was no significant limb by state interaction for hamstring or gastrocnemius flexibility, and no main effect of state was shown, suggesting that the hamstring and gastrocnemius flexibility may not be impacted by fatigue.

Limitations And Recommendations

Although participants ran continuously between trials and no rest intervals were permitted between testing at the fatigued state, one cannot rule out that some level of recovery occurred during the SEBT. Therefore, the fatigued state during the muscle flexibility test might be compromised. For the purpose of time, we only examined hamstring and gastrocnemius flexibility; therefore, we are unable to provide a global quality of lower-limb muscle flexibility. Also, practitioners need to be cautious when considering the skill level (competitive performers), sex, and participant age when utilizing the current findings in the field of youth sport training, as the participants in the present study were elite male athletes between 9 to 11 years of age. Future research with a larger sample size is needed to include competitive level, sex, and age as factors when examining the impact of fatigue on inter-limb asymmetry in functional performances. Findings would also need to be extended from Taekwondo to other sports.

Conclusions

Fatigue significantly impacts inter-limb asymmetry in jump performances and dynamic balance for child athletes, while the variation in inter-limb asymmetry caused by fatigue may be different across tests. The fatigue rates differ between the dominant and non-dominant leg, and more studies are needed to compare the fatigue rate between legs. For the purpose of injury prevention, practitioners should consider assessing the inter-limb asymmetry at both the rested and fatigued state for children, and be mindful of the fatigue response of each leg in functional tests.

Abbreviations

ANT: Anterior; CMJ: Countermovement jump; COM: Composite; ES: Effect size; ICC: Intra-class correlation coefficient; PL: Posterolateral; PM: Posteromedial; SD: Standard deviation; SEBT: Star Excursion Balance
Declarations

Ethics approval and consent to participate

The investigation received approval from, and was executed in exact accordance with, the ethical guidelines set forth by the University of British Columbia's Clinical Research Ethics Board for research involving human participants (CREB number: H19-02676). Written informed consent was received from parents/guardians of participants, and written informed assent was obtained from participants.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interest

The authors declare that they have no competing interests.

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Not applicable.

Authors’ contributions

GY contributed to the study design, data collection, data analysis and interpretation, and drafted the manuscript; BS, JQ, TJ, and WD contributed to the study design, data interpretation, and critical revision of the manuscript; LY, WN, WL contributed to data collection, data analysis, and critical revision of the manuscript. All authors read and approved the final manuscript.

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Tables
Table 1. Descriptive statistics for single-leg jump performance.

| Parameters      | Limb   | Rested state     | Fatigued state |
|-----------------|--------|------------------|----------------|
| CMJ (cm)<sup>a</sup> | D-Leg  | 14.31 ± 2.05*    | 12.77 ± 2.02   |
|                 | ND-Leg | 13.95 ± 2.80*    | 12.29 ± 2.68   |
| Hop (cm)<sup>a</sup> | D-Leg  | 130.48 ± 12.68*  | 119.97 ± 12.71 |
|                 | ND-Leg | 125.23 ± 15.06*  | 117.28 ± 17.58 |
| Triple Hop (cm)<sup>a</sup> | D-Leg  | 421.82 ± 31.61*  | 396.42 ± 32.02 |
|                 | ND-Leg | 410.44 ± 39.42*  | 378.26 ± 44.78 |

<sup>a</sup> Main effect of state.

* Significant difference between the rested and fatigued state.

CMJ = Single-leg countermovement jump; D-Leg = Dominant Leg; ND-Leg = Non-dominant Leg.

Table 2. Descriptive statistics for SEBT.

| Parameters      | Limb   | Rested state     | Fatigued state |
|-----------------|--------|------------------|----------------|
| ANT RD (%)<sup>a</sup> | D-Leg  | 108.25 ± 12.09*  | 103.50 ± 10.85 |
|                 | ND-Leg | 108.26 ± 12.14*  | 103.20 ± 9.61  |
| PM RD (%)<sup>a</sup> | D-Leg  | 89.79 ± 10.55*   | 84.93 ± 12.98  |
|                 | ND-Leg | 89.72 ± 10.93    | 88.80 ± 10.72  |
| PL RD (%)<sup>b,c</sup> | D-Leg  | 82.63 ± 12.56†   | 78.82 ± 15.97  |
|                 | ND-Leg | 75.91 ± 12.46    | 77.82 ± 14.20  |
| COM RD (%)<sup>a</sup> | D-Leg  | 91.94 ± 10.91    | 89.08 ± 12.12  |
|                 | ND-Leg | 91.30 ± 10.79    | 89.94 ± 9.92   |

<sup>a</sup> Main effect of state.

<sup>b</sup> Main effect of limb.
Significant interaction between limb dominance and state.

* Significant difference between rested and fatigued state.

† Significant difference between the dominant and non-dominant leg.

ANT = Anterior; PM = Posteromedial; PL = Posterolateral; COM = Composite; RD = Reach distance; D-Leg = Dominant Leg; ND-Leg = Non-dominant Leg.

Table 3. Descriptive statistics for flexibility test.

| Parameters      | Limb  | Rested state | Fatigued state |
|-----------------|-------|--------------|----------------|
| Hamstring (º)   | D-Leg | 67.77 ± 15.58| 64.38 ± 21.26  |
|                 | ND-Leg| 68.85 ± 14.67| 66.31 ± 18.83  |
| Gastrocnemius (º)| D-Leg | 45.54 ± 8.89 | 48.46 ± 7.47   |
|                 | ND-Leg| 46.62 ± 9.13 | 47.92 ± 7.94   |

D-Leg = Dominant Leg; ND-Leg = Non-dominant Leg.

Table 4. Variation in performance post fatigue (fatigue rate) and inter-limb asymmetry.
| Power     | Limb   | Fatigue rate (%) | State | Asymmetry (%) |
|-----------|--------|------------------|-------|---------------|
| CMJ       | D-Leg  | 11.56 ± 9.33     | Rested| 8.20 ± 11.97  |
|           | ND-Leg | 12.79 ± 9.64     | Fatigued| 12.76 ± 9.48 |
| Hop       | D-Leg  | 8.45 ± 4.52      | Rested| 6.64 ± 5.99   |
|           | ND-Leg | 6.91 ± 5.95      | Fatigued| 9.59 ± 4.79  |
| Triple Hop| D-Leg  | 6.17 ± 4.82      | Rested| 5.78 ± 6.41*  |
|           | ND-Leg | 8.36 ± 6.35      | Fatigued| 9.69 ± 6.45  |
| SEBT      | ANT RD | D-Leg  | 4.40 ± 6.95      | Rested| 8.36 ± 4.75*  |
|           |        | ND-Leg | 4.61 ± 7.36      | Fatigued| 3.71 ± 3.30  |
|           | PM RD  | D-Leg  | 5.96 ± 8.17      | Rested| 7.44 ± 5.83   |
|           |        | ND-Leg | 1.02 ± 6.95      | Fatigued| 10.67 ± 4.53 |
|           | PL RD  | D-Leg  | 5.58 ± 9.62†     | Rested| 9.97 ± 7.93   |
|           |        | ND-Leg | -2.17 ± 8.04     | Fatigued| 8.64 ± 6.18  |
|           | COM RD | D-Leg  | 5.13 ± 4.51      | Rested| 6.06 ± 4.08   |
|           |        | ND-Leg | 1.42 ± 3.71      | Fatigued| 4.03 ± 2.17  |
| Flexibility|       |       |                   |       |               |
| Hamstring | D-Leg  | 7.48 ± 16.84     | Rested| 8.32 ± 6.03   |
|           | ND-Leg | 5.21 ± 19.18     | Fatigued| 11.33 ± 8.62 |
| Gastrocnemius| D-Leg | -6.92 ± 14.92    | Rested| 7.85 ± 5.45   |
|           | ND-Leg | -3.12 ± 8.30     | Fatigued| 7.09 ± 6.25  |

CMJ = Single-leg countermovement jump; D-Leg = Dominant Leg; ND-Leg = Non-dominant Leg; ANT = Anterior; PM = Posteromedial; PL = Posterolateral; COM = Composite; RD = Reach distance; D-Leg = Dominant Leg; ND-Leg = Non-dominant Leg.

* Significant difference between the rested and fatigued state.

† Significant difference between the dominant and non-dominant leg.