symmetry

MDPI

Article

Inter-Limb Asymmetry in Force Accuracy and Steadiness Changes after a 12-Week Strength Training Program in Young Healthy Men

Rafał Szafraniec [1,*], Tadeusz Stefaniak [1], Dariusz Harmaciński [2] and Michał Kuczyński [3]

[1] Faculty of Physical Education and Sport Sciences, University School of Physical Education, 51-612 Wrocław, Poland; tadeusz.stefaniak@awf.wroc.pl
[2] Healthy Body Institute, 52-210 Wrocław, Poland; dariusz-harmacinski@wp.pl
[3] Faculty of Physiotherapy, University School of Physical Education, 51-612 Wrocław, Poland; michal.kuczynski@awf.wroc.pl
* Correspondence: rafal.szafraniec@awf.wroc.pl

Abstract: The study aimed to investigate the impact of a 12-week strength training program on force accuracy and steadiness changes in lower limbs in young healthy men. Twenty subjects with a dominant right lower limb were included. They performed a force matching task both pre and post strength training program. The ability to reproduce force was determined by calculating three errors: absolute error (AE), constant error (CE), and variable error (VE). After intervention AE and VE improved in both legs indicating higher improvement in the dominant leg ($p = 0.032$ for AE and $p = 0.005$ for VE). However, CE improved only in the dominant leg ($p = 0.001$). We conclude that strength training improved the accuracy and consistency of force in a force reproduction task. This improvement was more evident in the dominant lower limb. Most likely, the inter-limb asymmetry in changes of force application ability caused by strength training is due to the different mechanisms responsible for the control of voluntary movements in the dominant and non-dominant lower limb.

Keywords: force sense; force matching task; force reproduction; force errors; lower extremities; resistance training

check for updates

Citation: Szafraniec, R.; Stefaniak, T.; Harmaciński, D.; Kuczyński, M. Inter-Limb Asymmetry in Force Accuracy and Steadiness Changes after a 12-Week Strength Training Program in Young Healthy Men. *Symmetry* **2021**, *13*, 2226. https://doi.org/10.3390/sym13112226

Academic Editor: John H. Graham

Received: 6 October 2021
Accepted: 17 November 2021
Published: 21 November 2021

1. Introduction

The senses of effort, force, and heaviness, along with the senses of balance and kinesthesia are manifestations of proprioception [1], which plays an important role in neuromuscular control, movement coordination, and precision. Accurate and sometimes symmetrical force application is crucial not only in sports (e.g., powerlifting), but also in everyday activities (e.g., carrying a tray of drinks with both hands). We learn how important these abilities are when they become affected. It is for this reason that an overwhelming amount of research on force application ability has been conducted on patients in whom this ability has been impaired as a result of injury or disease. This issue has been studied in patients with tearing of the anterior cruciate ligament [2], patellofemoral pain syndrome [3], functional ankle instability [4], rotator cuff tendinopathy [5], or spastic hemiplegia [6]. In the case of unilateral injury/dysfunction, the goal of rehabilitation is to achieve performance at a level similar to the healthy side, which we consider to be a kind of reference. Therefore, increased intra-limb functional symmetry could be considered as a marker of successful rehabilitation.

To improve the accuracy of force application, various force plates with audio and/or visual feedback of the applied force are used [7]. However, these devices are quite expensive and not widely available. It seems reasonable to ask whether a similar goal can be achieved with traditionally used physical exercises, such as strength training. So far, published studies do not provide conclusive results. On one hand, a six-week strength training protocol did not improve force accuracy and steadiness in participants with functional ankle instability [4]. On the other hand, a 10-week strength training improved submaximal force control in aged adults [8].

Accurate dosing and reproduction of force are important not only for patients, but also for athletes, as they determine the correct performance of a technical task in any sport [9,10]. On the other hand, poor force matching ability increases the risk of injury [11,12]. So far, there is no evidence on the impact of strength training on force accuracy and steadiness in a young and healthy population. Strength training is an essential part of the training in most sports and its main goal is to build hypertrophy, muscle strength, and power [13]. The question is whether repeated muscle stimulation with a heavy load also affects force accuracy and steadiness. Another question that arises is whether strength training will cause similar changes in force matching ability in the dominant and nondominant limb. The rationale for this question is based on the fact that inter-limb asymmetries have been found in muscle strength, sprinting, dynamic balance, sport-specific actions, and anthropometry [14–16]. In addition, studies indicate the existence of different mechanisms responsible for the control of voluntary movements in the dominant and non-dominant lower limb [17]. The answer to these questions will provide valuable information to athletes and strength and conditioning coaches about the additional properties of strength training, taking into account the potential inter-limb asymmetries. This can be especially important in sports that favor the dominance of one limb over the other. Additionally, information about possible inter-limb asymmetry in response to strength training may be useful when planning rehabilitation for patients with the aforementioned dysfunctions. Therefore, the purpose of our work was to investigate the impact of a 12-week strength training program on force accuracy and steadiness changes in lower limbs in young healthy men.

2. Materials and Methods

2.1. Study Design

A pretest–posttest study design with two groups (non and dominant leg) was used to determine the impact of a 12-week strength training program on force accuracy and steadiness. The measurement of force reproduction ability was carried out twice: one week before the training program (Pre) and one week after completing the training program (Post). To investigate the force accuracy and steadiness, subjects performed five repeated tasks of matching the target force (50% MIVC—maximal isometric voluntary contraction) by pressing a force plate for 3 s with each leg in randomized order. We used three types of errors as measures of force accuracy and steadiness: absolute error (AE), constant error (CE), and variable error (VE).

2.2. Participants

Twenty male healthy adults (age 21.4 ± 2.2 years; body mass 76 ± 8.4 kg; height 180.1 ± 7.3 cm; BMI 23.5 ± 2.4 kg/m^2) voluntarily participated in the experiment. They gave their informed consent to the experimental procedure. The study procedures and informed consent were approved by the Bioethics Committee of the Medical Chamber in Opole in accordance with the Declaration of Helsinki (registration number: 151/2007). Inclusion criteria were: age 19–24 years; male; healthy; not a professional athlete; active lifestyle (1.5 h of physical activity at least 3 times a week); dominant right lower limb [18]. Exclusion criteria: injury (acute or chronic); any pathology that could affect the ability to perform the experiment; absence for more than 6 training units.

2.3. Measurement of Force Accuracy and Steadiness

For this purpose, tests were used to assess the ability to reproduce a previously generated and predetermined sub-maximal quantity of force [19].

The testing equipment consisted of a seat and two boards which were each attached to strain gauges MVD 2555 (Hottinger Baldwin Messtechnik, Darmstadt, Germany) and connected in a full-bridge configuration (Figure 1). The signal of pressure was sent from the strain gauges to the computer via an amplifier and an AD/DA card.

Figure 1. Equipment for measurements of force accuracy and steadiness (own source).

Initially, the maximum isometric voluntary contraction (MIVC) was measured for each leg. Subjects assumed the position by resting their backs against the seat backrest. The tested leg was placed on a dedicated pad attached to the board, while the untested leg rested on the ground. The knee joint was flexed to an angle of 60°. The correct angle was obtained by moving the seat linearly and was checked using an electronic goniometer attached with Velcro to the legs. The arms of the goniometer were attached to the thigh and shank in such a way that the axis of rotation of the goniometer coincided with the axis of rotation of the knee joint in the sagittal plane. Three MIVCs of 3 s duration were carried out by each leg in random order. The rest period between testing the dominant and non-dominant leg was 30 s. The mean force value for each trial was calculated and then the highest score from the three trials was used to determine the target force (50% MIVC) that subjects were expected to reproduce.

Then, subjects were asked to develop 50% MIVC tension for 3 s. During the initial learning phase (5 repetitions for each leg), subjects were provided with visual feedback to help them achieve a correct match (50% MIVC). During testing, visual feedback was not provided. Subjects performed 5 repetitions of target force 50% MIVC held for 3 s with each leg in randomized order. The intra-limb rest was 10 s and the inter-limb rest was 30 s. The force signal was sampled at 100 Hz. The mean value of force for each 3-s trial was recorded.

The measurements were carried out twice: one week before the training program (Pre) and one week after completing the training program (Post). We performed the Post-test one week after completing the training program to allow the subjects full recovery after the last training unit, as fatigue deteriorates proprioceptive sense [1]. Measurements of force accuracy and steadiness always took place in the morning without warming up.

2.4. Strength Training Program

One week prior to strength training, all subjects were instructed on the technique of each exercise by a qualified instructor. The same instructor supervised the correctness of the exercise technique throughout the study. Participants performed a strength-training program involving the muscles of the upper and lower extremities and the torso. On each training unit, only exercises from variant A (upper extremities and torso) or B (lower extremities and torso) were performed. Exercise variants were performed alternately in the following training days. Exercises of variant A included: bench press, seated behind the neck press, wide grip pull-down, roman chair legs lift, and crunches. Exercises of variant B included: barbell half squat, deadlift, barbell reverse lunge, side crunches, and weighted sit-ups. For each exercise, the one-repetition maximum (1RM) test was completed one week prior to the study, and then 1RM was re-measured every 2 weeks throughout the study to adjust loads [20].

Exercises for the lower and upper extremities were performed according to the following scheme: 3 sets × 3 reps × 60% 1RM, 1 set × 3 reps × 80% 1RM, 1 set × 2 reps × 90% 1RM, 1 set × 2 reps × 95% 1RM, 2 sets × 1 rep × 100% 1RM, 2 sets × 2 reps × 90% 1RM. Torso muscle exercises (legs lifts, crunches, and sit-ups) were performed with the maximum number of repetitions. Each participant performed the workout 3 times a week (Monday/Wednesday/Friday) for 12 weeks. All training sessions were held at the same time of the day.

2.5. Data Analysis

The performance in the force matching task was determined by means of three errors: absolute error (AE), constant error (CE), and variable error (VE).

$$\mathrm{AE} = \left| \frac{\sum(x_i - T)}{n} \right| \tag{1}$$

$$\mathrm{CE} = \frac{\sum(x_i - T)}{n} \tag{2}$$

$$\mathrm{VE} = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n}} \tag{3}$$

where x_i is the force reproduced in trial i, $\overline{x}$ is the mean value of force from five trials, T is the target force (50% MIVC [N]), and n is the number of trials. Then, the errors were divided by the target force resulting in the relative percentage values. The AE determines the individual's accuracy in reproducing force, VE determines the steadiness of the reproductions performed, and CE determines the tendency to reproduce the force above or below the target [2]. In other words, CE indicates the directionality, undershoot (negative values), or overshoot (positive values) of the target [12].

2.6. Statistics

The Shapiro–Wilk test was applied to assess the normality of dependent variables indicating that they did not differ significantly from the normal distribution. Thus, a repeated-measure ANOVA with two factors: Time (pre- and post-training) and Leg (dominant and non-dominant) was used to evaluate possible main effects and interactions. Tukey's post-hoc multiple comparisons were performed if a significant main effect was observed. For each ANOVA, partial eta-squared were calculated as measures of the effect size. Values of 0.01, 0.06, and above 0.14 were considered as small, medium, and large, respectively. The statistical analyses were performed using the Statistica 13.1 software (Dell, Round Rock, TX, USA). The level of significance was set at 0.05.

3. Results

As a result of strength training, a significant increase in MIVC was observed. The exercises strengthened the dominant leg by 27% and the non-dominant leg by 35%. Participation in the exercises resulted in a number of favorable changes in the performance of the force reproduction task, which are presented below.

There were two main effects on the absolute error (force accuracy): Time (F(1, 19) = 58.060, $p < 0.001$, $\eta^2 = 0.753$) and Leg (F(1, 19) = 5.055, $p = 0.037$, $\eta^2 = 0.210$). The former indicated that training improved the accuracy on average from 20 to just over 5% of the predefined targets, whereas the latter showed the overall lower absolute error for the dominant limb. This advantage of the dominant over the non-dominant limb resulted only from the unequal improvement in force reproduction given by Time x Leg interaction (F(1, 19) = 7.505, $p = 0.013$, $\eta^2 = 0.283$) in favor of the dominant leg. This was further supported in the post-hoc analysis

(Table 1) which indicated that the final post-training performance was better for the dominant than the non-dominant leg ($p = 0.032$).

Table 1. Comparison of MIVC and the relative errors in force reproduction with the non-dominant and dominant lower limb, before and after strength training.

	Non-Dominant Limb		Dominant Limb	
	Pre	**Post**	**Pre**	**Post**
MIVC (N)	724.5 (153.0)	981.0 (108.0) **	904.5 (162.0) ǂǂ	1147.5 (45.0) **ǂǂ
AE (%)	19.14 (7.85)	9.54 (4.75) *	21.12 (11.20)	2.35 (1.76) **ǂ
VE (%)	13.73 (5.26)	7.60 (2.87) *	11.03 (4.65)	2.42 (2.14) **ǂǂ
CE (%)	−13.86 (14.37)	−4.26 (8.67)	−19.88 (12.52)	−1.33 (1.79) *

Mean (SD), * significant between time difference (* $p < 0.005$, ** $p < 0.001$); ǂ significant between limb difference (ǂ $p < 0.05$, ǂǂ $p < 0.005$).

There were also two main effects on the variable error (consistency). Time (F(1, 19) = 86.500, $p = 0.001$, $\eta^2 = 0.820$), i.e., participation in the strength training, improved consistency, after collapsing over limbs, from just over 12 to 5% of the mean value of the 5 performed trials. The Leg effect (F(1, 19) = 20.768, $p < 0.001$, $\eta^2 = 0.522$) showed the overall lower variable error for the dominant limb. The rate of improvement was similar in both lower limbs ($p < 0.001$ for the dominant and $p = 0.001$ for the non-dominant limb). Yet, the post-training consistency was better in the dominant than in the non-dominant limb ($p = 0.005$). This confirmed the advantage of the dominant over the non-dominant leg in the force reproduction task after the training (Table 1).

The constant error showed the main effect of Time (F(1, 19) = 40.361, $p < 0.001$, $\eta^2 = 0.680$), which indicated that strength training increased accuracy from about −17 to −3% after collapsing over limbs. Although there was no significant Time x Leg interaction, it was only the dominant limb that improved its constant error ($p = 0.001$), whereas the change in the non-dominant limb performance in force reproduction was insignificant (Table 1).

4. Discussion

Our study aimed to investigate the impact of a 12-week strength training program on force accuracy and steadiness changes in lower limbs. There are two results that seem particularly interesting. First, all the error measures that we used showed no differences between the limbs in the performance of the force reproduction task at baseline. This means that young men who have not undertaken specific and sustained physical activity for a long time perform this task with each limb at a similar level. Second, the same error measures confirmed that participation in a three-month strength training revealed the advantage of the dominant leg over the non-dominant leg in the performance of the same task. There is no interpretation other than the finding of asymmetry in learning this motor task.

The three different measures of performance at baseline showed that the force reproduction task carried out by each leg resulted in similar errors. The force actually applied by the subjects was lower than the target force (negative values of CE), indicating that they overestimated the force produced which concurs with other studies investigating similar tasks performed by upper [21] and lower extremities [22]. The errors of our participants seem even slightly higher, which could have been caused by a more difficult task involving more joints rather than one joint in other studies [18,22]. Due to very moderate physical activity for several months before commencing this study, the homogeneous performance of the dominant and non-dominant limb appears to be the result of the gradual fine-tuning of both legs, although the respective neural mechanisms may differ slightly.

The changes caused by training have both positive and negative characteristics. Undoubtedly, the increase in the accuracy of the task performed and a significant reduction in variability for both legs is positive. However, at the same time, the disproportions between the two legs became visible. The results (Table 1) clearly show that the relative decrease in the values of all percentage errors was much greater for the dominant than for the non-dominant limb. Our data do not allow us to explain the reasons for these discrepancies. For example, the learning process may be longer for the non-dominant limb and prolonged training may further improve its performance [23]. It is also possible that the refinement process has come to a halt during training to maintain an elevated value of motor variability that may be desirable for some function of this leg. Nevertheless, the presence of such a limitation for the non-dominant leg in force matching tasks may be of importance in some applications as rehabilitation.

Our results are not consistent with those achieved by Hortobágyi et al. who stated that the significant reductions in force error with training were limited to dynamic contractions (eccentric and concentric), with no change observed in the isometric condition [8]. In our study, we measured force errors under isometric conditions and we found improved force accuracy and steadiness after strength training, however, demonstrated mainly in the dominant limb. This dominant limb advantage is easy to observe in Table 1, although specific changes in each error indicate slightly different levels of this improvement. The discrepancy between the results of Hortobagyi et al. [8] and ours may be due to differences in the exercise protocols and subjects. Hortobagyi et al. used only bilateral supine leg press performed by older people, whereas in our study, we used a set of free-weight exercises. The use of free-weights during resistance training imposes greater mechanical demands on the body due to the center of mass of the total system being further away (higher) from the base of support and, in turn, challenges postural stability [13]. Control of the shifting weight to maintain balance requires contractions of large agonists and stabilizers, which should occur in a timely manner and with precisely dosed force. Tensions, especially of stabilizers, occur under isometric conditions. It is in the use of exercises with free weights that we see a potential reason for the difference between our results and those obtained by Hortobagyi et al. [8].

The problem of the relationship between force errors and maximal strength also seems interesting. However, the available results are inconclusive. Hortobágyi et al. found that force steadiness (variability) was not related to maximal strength [8]. In contrast, Kaynak et al. found that the participants with higher MVIC values had higher force replication errors [24]. Both studies examined the strength and force errors in the dominant limb only. Our results show a greater increase in MVIC in the non-dominant leg than in the dominant leg (35% vs. 27%). On the other hand, considering the force errors, it was the dominant leg that showed a greater improvement. This asymmetry between MIVC and force errors scores may therefore indicate that force application ability does not depend on the maximal strength, but rather on the tasks that the limb has to perform. The dominant limb is the mobilizing limb and is used in activities requiring precision [25], while the limb used to provide postural support during the activities performed by the manipulative limb is defined as the non-dominant one [26]. Regardless of whether humans produce maximal or submaximal forces, limb force asymmetry appears to be related to neural factors rather than differences in mechanical capabilities between the limbs [27].

There are very few papers on asymmetries in force application ability in the lower extremities. Most studies focus on the inter-limb asymmetry in strength, power, and physical performance [14,28]. We were able to find only one paper [26] that partially confirms our results about higher force accuracy in the dominant limb. However, in that study, the subjects were female soccer players in whom the problem of symmetry/asymmetry of force application ability in the lower limbs is of particular importance due to the specific motor tasks that a soccer player must perform on the field, i.e., kicks, running with frequent and rapid changes of direction. Considerably more research can be found regarding asymmetries in force reproduction accuracy and steadiness in the upper extremities [29–31]. It is suggested that the non-dominant hand may use a combination of efferent copy and proprioceptive feedback and the force matching is based on feedback control, whereas the dominant hand may primarily use the efferent copy of the reference motor command to perform the force matching task and the execution is performed in a feedforward manner [30,32]. If we were to accept this theory to explain our findings, which indicate that force accuracy and consistency increased after strength training primarily in the dominant leg, this would indicate that strength training was more likely to improve the efferent mechanisms responsible for generating adequate force than the efficiency of using afferent feedback in performing the force matching task.

A limitation of our study may regard the lack of a reference group that could help assess the validity of the alternative hypothesis that the obtained result was caused solely by exercise without weights. We could also consider using a control group that would perform single-leg balance training to assess the effect of proprioception on the ability to reproduce force. Although apparently secondary, this problem may become more important for certain patient populations. The observed inter-limb asymmetry in improvements in force accuracy and consistency that occurred as a result of strength training should be a consideration when planning the duration and effects of rehabilitation. This is because the time required to improve force accuracy may depend on whether the impaired limb is dominant or nondominant. This issue certainly requires further research to clarify the mechanisms responsible for the observed asymmetry. To summarize, it seems that any sufficiently intense training involving joint movement (often referred to as proprioceptive training) might lead to beneficial changes in some aspects of proprioception. It remains to be assessed which combination of such free exercises and strength exercises is optimal for the target group of athletes or patients.

5. Conclusions

Strength training improves the accuracy and consistency of the force reproduction task. This improvement is more pronounced in the dominant lower limb. Most likely, the inter-limb asymmetry in changes of force application ability caused by strength training is due to the different mechanisms responsible for the control of voluntary movements in the dominant and non-dominant lower limb, which in turn is related to the functional specialization of both limbs.

Author Contributions: Conceptualization, R.S., T.S., D.H. and M.K.; Methodology, T.S., D.H. and M.K.; Validation, D.H.; Formal analysis, R.S. and M.K.; Investigation, T.S. and D.H.; Resources, R.S. and M.K.; Data curation, M.K.; Writing—Original draft preparation, R.S. and M.K.; Writing—Review and editing, R.S., T.S., D.H. and M.K.; Visualization, R.S.; Supervision, R.S. and M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Bioethics Committee of the Medical Chamber in Opole (protocol code: 151, date of approval: 12 December 2007).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Proske, U.; Gandevia, S.C. The Proprioceptive Senses: Their Roles in Signaling Body Shape, Body Position and Movement, and Muscle Force. *Physiol. Rev.* **2012**, *92*, 1651–1697. [CrossRef]
2. Godinho, P.; Nicoliche, E.; Cossich, V.; de Sousa, E.B.; Velasques, B.; Salles, J.I. Proprioceptive deficit in patients with complete tearing of the anterior cruciate ligament. *Rev. Bras. Ortop.* **2014**, *49*, 613–618. [CrossRef]
3. Salahzadeh, Z.; Maroufi, N.; Salavati, M.; Aslezaker, F.; Mortaza, N.; Hachesu, P.R. Proprioception in Subjects with Patellofemoral Pain Syndrome: Using the Sense of Force Accuracy. *J. Musculoskelet. Pain* **2013**, *21*, 341–349. [CrossRef]
4. Smith, B.I.; Docherty, C.L.; Simon, J.; Klossner, J.; Schrader, J. Ankle Strength and Force Sense After a Progressive, 6-Week Strength-Training Program in People with Functional Ankle Instability. *J. Athl. Train.* **2012**, *47*, 282–288. [CrossRef] [PubMed]
5. Maenhout, A.G.; Palmans, T.; De Muynck, M.; De Wilde, L.F.; Cools, A.M. The impact of rotator cuff tendinopathy on proprioception, measuring force sensation. *J. Shoulder Elb. Surg.* **2012**, *21*, 1080–1086. [CrossRef] [PubMed]

6. Yen, J.; Li, S. Altered force perception in stroke survivors with spastic hemiplegia. *J. Rehabil. Med.* **2015**, *47*, 917–923. [CrossRef] [PubMed]
7. Simon, A.M.; Gillespie, R.B.; Ferris, D.P. Symmetry-based resistance as a novel means of lower limb rehabilitation. *J. Biomech.* **2007**, *40*, 1286–1292. [CrossRef] [PubMed]
8. Hortobágyi, T.; Tunnel, D.; Moody, J.; Beam, S.; DeVita, P. Low- or High-Intensity Strength Training Partially Restores Impaired Quadriceps Force Accuracy and Steadiness in Aged Adults. *J. Gerontol. Ser. A Boil. Sci. Med. Sci.* **2001**, *56*, B38–B47. [CrossRef]
9. Niespodziński, B.; Kochanowicz, A.; Mieszkowski, J.; Piskorska, E.; Żychowska, M. Relationship between Joint Position Sense, Force Sense, and Muscle Strength and the Impact of Gymnastic Training on Proprioception. *BioMed Res. Int.* **2018**, *2018*, 1–10. [CrossRef] [PubMed]
10. Sevrez, V.; Bourdin, C. On the Role of Proprioception in Making Free Throws in Basketball. *Res. Q. Exerc. Sport* **2015**, *86*, 274–280. [CrossRef]
11. Ozer, D.; Duzgun, I.; Baltaci, G.; Karacan, S.; Colakoglu, F. The effects of rope or weighted rope jump training on strength, coordination and proprioception in adolescent female volleyball players. *J. Sports Med. Phys. Fit.* **2011**, *51*, 211.
12. Trousset, K.; Phillips, D.; Karduna, A. An Investigation into Force Sense at the Shoulder. *Mot. Control.* **2018**, *22*, 462–471. [CrossRef] [PubMed]
13. Szafraniec, R.; Bartkowski, J.; Kawczyński, A. Effects of Short-Term Core Stability Training on Dynamic Balance and Trunk Muscle Endurance in Novice Olympic Weightlifters. *J. Hum. Kinet.* **2020**, *74*, 43–50. [CrossRef] [PubMed]
14. Bishop, C.; Turner, A.; Read, P. Effects of inter-limb asymmetries on physical and sports performance: A systematic review. *J. Sports Sci.* **2018**, *36*, 1135–1144. [CrossRef] [PubMed]
15. Seminati, E.; Nardello, F.; Zamparo, P.; Ardigò, L.P.; Faccioli, N.; Minetti, A.E. Anatomically Asymmetrical Runners Move More Asymmetrically at the Same Metabolic Cost. *PLoS ONE* **2013**, *8*, e74134. [CrossRef] [PubMed]
16. Franco-García, J.M.; Rodal, M.; Gutiérrez-Horrillo, R.; Carlos-Vivas, J.; Pérez-Gómez, J.; Nobari, H.; Ardigò, L.P.; Gianikellis, K. Shoulder Kinematics and Symmetry at Different Load Intensities during Bench Press Exercise. *Symmetry* **2021**, *13*, 1859. [CrossRef]
17. Arboix-Alió, J.; Buscà, B.; Busquets, A.; Aguilera-Castells, J.; De Pablo, B.; Montalvo, A.M.; Fort-Vanmeerhaeghe, A. Relationship between Inter-Limb Asymmetries and Physical Performance in Rink Hockey Players. *Symmetry* **2020**, *12*, 2035. [CrossRef]
18. Furmanek, M.P.; Słomka, K.; Sobiesiak, A.; Rzepko, M.; Juras, G. The Effects of Cryotherapy on Knee Joint Position Sense and Force Production Sense in Healthy Individuals. *J. Hum. Kinet.* **2018**, *61*, 39–51. [CrossRef] [PubMed]
19. Röijezon, U.; Clark, N.; Treleaven, J. Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. *Man. Ther.* **2015**, *20*, 368–377. [CrossRef] [PubMed]
20. Seo, D.-I.; Kim, E.; Fahs, C.A.; Rossow, L.; Young, K.; Ferguson, S.L.; Thiebaud, R.; Sherk, V.D.; Loenneke, J.P.; Kim, D.; et al. Reliability of the One-Repetition Maximum Test Based on Muscle Group and Gender. *J. sports Sci. Med.* **2012**, *11*, 221–225.
21. Timmons, M.K.; Stevens, S.M.; Pincivero, D.M. The effect of arm abduction angle and contraction intensity on perceived exertion. *Graefe's Arch. Clin. Exp. Ophthalmol.* **2009**, *106*, 79–86. [CrossRef]
22. Lauziere, S.; Dubois, B.; Briere, A.; Nadeau, S. Magnitude of force perception errors during static contractions of the knee extensors in healthy young and elderly individuals. *Atten. Percept. Psychophys.* **2011**, *74*, 216–224. [CrossRef] [PubMed]
23. Cheng, L.; Chang, S.; Youlian, H.; Hong, Y. Effects of different periods of Tai Chi exercise on the kinesthesia of the lower limb joints of elderly women. *Res. Sports Med.* **2017**, *25*, 462–469. [CrossRef] [PubMed]
24. Kaynak, H.; Altun, M.; Tok, S. Effect of Force Sense to Active Joint Position Sense and Relationships between Active Joint Position Sense, Force Sense, Jumping and Muscle Strength. *J. Mot. Behav.* **2020**, *52*, 342–351. [CrossRef] [PubMed]
25. Forczek, W.; Staszkiewicz, R. An Evaluation of Symmetry in the Lower Limb Joints During the Able-Bodied Gait of Women and Men. *J. Hum. Kinet.* **2012**, *35*, 47–57. [CrossRef] [PubMed]
26. Iwańska, D.; Karczewska, M.; Madej, A.; Urbanik, C. Symmetry of proprioceptive sense in female soccer players. *Acta Bioeng. Biomech.* **2015**, *17*, 155–163. [CrossRef] [PubMed]
27. Simon, A.M.; Ferris, D.P. Lower limb force production and bilateral force asymmetries are based on sense of effort. *Exp. Brain Res.* **2008**, *187*, 129–138. [CrossRef]
28. Pardos-Mainer, E.; Casajús, J.A.; Bishop, C.; Gonzalo-Skok, O. Effects of Combined Strength and Power Training on Physical Performance and Interlimb Asymmetries in Adolescent Female Soccer Players. *Int. J. Sports Physiol. Perform.* **2020**, *15*, 1–9. [CrossRef] [PubMed]
29. Mitchell, M.; Martin, B.J.; Adamo, D.E. Upper Limb Asymmetry in the Sense of Effort Is Dependent on Force Level. *Front. Psychol.* **2017**, *8*, 643. [CrossRef]
30. Scotland, S.; Adamo, D.E.; Martin, B.J. Sense of effort revisited: Relative contributions of sensory feedback and efferent copy. *Neurosci. Lett.* **2014**, *561*, 208–212. [CrossRef]
31. Adamo, D.E.; Scotland, S.; Martin, B.J. Asymmetry in grasp force matching and sense of effort. *Exp. Brain Res.* **2012**, *217*, 273–285. [CrossRef] [PubMed]
32. Sainburg, R.L. Handedness: Differential Specializations for Control of Trajectory and Position. *Exerc. Sport Sci. Rev.* **2005**, *33*, 206–213. [CrossRef] [PubMed]