HUMAN MOVEMENT
2017; 18(2): 30–37

ACCURACY OF FORCE REPEATABILITY IN RELATION TO ITS VALUE AND THE SUBJECTS' SEX

original paper
doi: 10.1515/humo-2017-0017

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ABSTRACT
Purpose. The purpose of the study was to determine the influence of force value and sex on force generation repeatability.
Methods. The total of 17 female and 24 male students performed 3 maximal voluntary contractions for maximal force (F_{max}) calculation and 10 isometric contractions with targeted forces of 49 N, 98 N, 147 N by arms: elbow extension (EE), elbow flexion (EF) and legs: knee extensions (KE). Variation in repeatedly generated forces is expressed as a coefficient of variation.
Results. The force generation repeatability rose with the increase of triggered force in both sexes; between force target 49 N vs. 98 N and 147 N ($p < 0.00$) for EE and EF in females, between 49 N vs. 147 N for all measurements ($p < 0.00$) except the right elbow extension in males. We noticed minor sex influence on force generation repeatability for EE, EF, and KE in absolute measured values and relatively to F_{max}.
Conclusions. The influence of force value and a minor influence of sex on accuracy in generated forces might suggest that the control of muscle force by the central nervous system is similar in both sexes and the sex differences in muscle force generations are rather of muscle mass and structure.
Key words: isometric force, force repeatability, gender, elbow flexion, elbow extension, knee extension

Introduction

Force is an essential component of movement execution. The study of gender differences in respect to muscle force, in both absolute and relative force generation ability, were the subject of several studies [1–6] and some of them documented sex differences [1, 5, 7]. These differences arise from the differences in body composition [6] as well as structural and functional parameters of muscles [3, 4]. The major contributing factor, taking into account sex differences in force production, is the greater muscle mass in males; muscle mass constitutes 36–45% of body mass in men and 32–36% in women. Even if muscle mass is adjusted to body mass [8], or to the ratio of fat-free body mass [9], men still manifest higher muscle force. The assessment of maximal force in relation to the muscle cross-section also revealed greater force in men [1].

Considering the muscle morphology, there are two factors determining the contraction force: muscle structure (its cross-sectional area, length of fibres and angular pennation [3, 4]) and its intracellular structure [10]. Differences in muscle structures depend on the muscle [11]. Angular pennation in the triceps brachii muscle in both sexes is similar and it has a smaller influence on the capability to generate force than the size of the muscle [3]. In turn, sonographic tests by Chow et al. [4] showed statistically significant differences between the sexes in the structure of the gastrocnemius and the posterior soleus muscles. In women, the fibres were longer while in men the fibre pennation angle was bigger [3, 4]. A smaller area of the muscle cross-section, a smaller number of muscle fibres, and a smaller capacity of muscle glycolytic sources result in lower muscle force in women [8].

The sense of force commonly assessed by force repeatability (FR) has been a subject of numerous studies in various aspects. Most of the research refers to the examination of the possibility to maintain the targeted force level, e.g. by elbow flexor muscles [12, 13] or knee extensor muscles [5]. Limb FR in this study was examined with the use of reference force determined as a percentage of isometric maximal voluntary contraction (IMVC), which is the most popular method. The study was also dedicated to the examination of separated muscle groups by specific stabilization of the limbs.

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Received: February 8, 2016
Acepted for publication: May 30, 2017

Citation: Błacha R, Jastrzębska AD. Accuracy of force repeatability in relation to its value and the subjects' sex. Hum Mov. 2017;18(2):30–37; doi: 10.1515/humo-2017-0017.

Since in everyday life people perform tasks requiring various muscle activation, and the starting positions may vary, in the presented study we evaluated the capability of isometric FR without limb stabilization. Despite the use of isometric force in this study, each generated force was preceded by position adoption of the examined body part before the force generation movement was allowed. We are aware that this freedom can influence the results because of different joint angles and muscle activation strategies used to achieve the target force level. However, independently of the situation, balanced muscle activity within force couples should be reached. According to Schmidt's [14] schema theory, there is an infinite number of strategies utilized to activate muscles during the course of tasks. The human movement variability can be described as a normal variation across multiple repetitions of the same task. Therefore, we were interested in the ability to FR regardless of the strategy chosen by the nervous system to perform the task. Since the parameters that can be changed are the force and movement time, we decided to measure force generation [15]. While analysing the differences between both sexes in muscle force production we wondered whether similar differences were observed in the precision of muscle FR. According to Stevens's power law, equal stimulation ratios yield equal response ratios [16]; the perception of increments in muscle force grows exponentially. Thus, the repeatability should rise with a concomitant increase of targeted force. In this paper, we tried to assess the precision in repeatability with which men and women were able to generate the target force at three given levels, without visual feedback. We believe that this can be a complement to the existing research on force generation sense in relation to the participants' sex.

Material and methods

Participants

The total of 17 females and 24 males with no history of musculoskeletal injury and neurological disorders volunteered to participate in the study. All participants were students of the University of Physical Education in Wroclaw, Poland and were informed about the nature of study. They provided their written consents to participate in the study. The study protocol was approved by the local Ethics Committee. All subjects were right-handed and right-legged. The dominance of arm was determined by tests of writing and throwing a ball, leg dominance was established by jump on one leg test and take a step forward test. The average age, height, and body mass were 21.9 ± 2.1 years, 1.63 ± 0.06 m, 56.8 ± 6.1 kg for the women; and 20.6 ± 1.7 years, 1.81 ± 0.08 m, 75.3 ± 6.4 kg for the men, respectively.

Apparatus and procedure

The kinaesthesiometer station (Figure 1) consisted of a chair and three force transducers – separate ones for the upper limbs and one for the lower limbs. Force transducers for the upper limbs allow recording of force production in the forward-backward direction (elbow extension-flexion). The transducer for the lower limbs allows to record force generated in knee extension. The chair was adjusted to individual anatomy through the regulatory system (movable back and seat) to ensure proper angles in joints during measurements: elbow at the angle of 90°, lower limbs at the knee at the angle of 100°, and feet rested at the angle of 90° in relation to the shin. The forearm was positioned in pronation. During each examination arms and legs were not strapped to the force transducer. Nevertheless, this freedom can influence the results because of different joint angles and muscle activation strategies used to achieve the target force level. We were interested in the participants' ability to repeat the sub-maximal force requested rather than the strategy of the nervous system in which the target is to be achieved. However, in normal life we deal with different conditions, thus the proper force is generated by various strategies.

The station was connected (through an amplifier) to a computer with an analog-digital card (A/C Advantech 1716L) and Kinesthesiometer software, version 1 (Wroclaw, Poland) to archive the results in a database

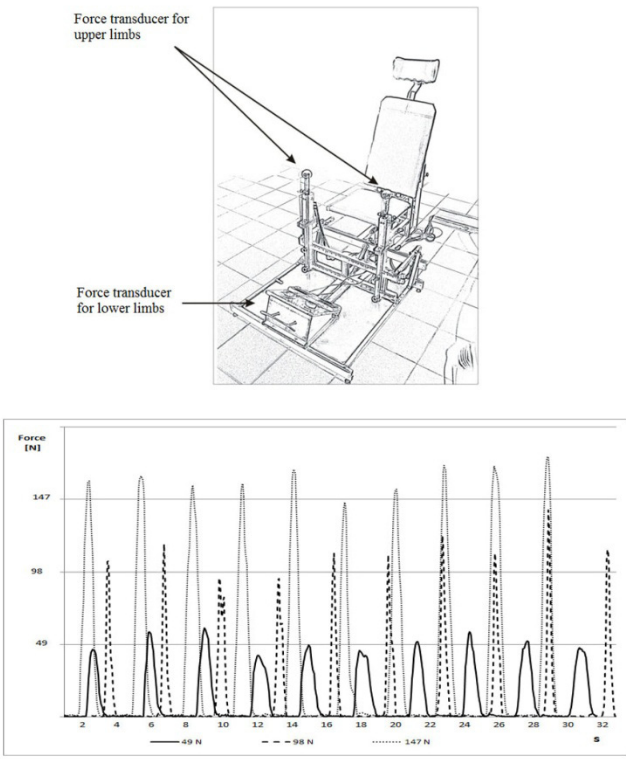


Figure 1. The force measurement station and an example of a typical force-time curve during the force sense examination for three target levels

and perform initial data analysis (calculation of mean and standard deviation for the triggered forces).

Isometric maximal voluntary contraction measurement

The IMVC force (F_{max}) was determined as the highest value within three measurements, each of 3-second duration followed by a 30-second rest period. During F_{max} examination, verbal encouragement and visual feedback was displayed on a monitor placed at the distance of 1 m in front of the station.

Isometric sub-maximal force repeatability measurement

The FR was measured during sub-maximal trials. In each trial, the participants were to repeat the target force 10 times. The given target forces were 49 N (5 kG), 98 N (10 kG), and 147 N (15 kG), and the FR was measured respectively in extension and flexion contractions of the upper limbs and in extension contractions of the lower limbs. The measurements were performed in the following sequence: right elbow extension (REE), right elbow flexion (REF), left elbow extension (LEE), left elbow flexion (LEF), right knee extension (RKE) and left knee extension (LKE). The intervals between the examinations of each load lasted 20 minutes. Before each sub-maximal trial, each participant performed 5 test pushes against the force transducers in order to remember the target force. A marked blue line on the screen 1 m away from the subject provided the visual feedback. Before each examination, the station was calibrated with 5 kg, 10 kg, or 15 kg weight depending on the triggered force.

The main examination was carried out without visual feedback, as the screen was turned round. Participants were told to place their left hand on their laps, and their right arm in the pronated position on the force transducer. The participants were instructed to reach the indexed peak of force (49 N, 98 N, and 147 N) as fast as possible and after that left the force transducer as fast as possible so as to focus on the capability to reproduce the required force. Figure 1 illustrates the data sample.

The mean of 10 isometric muscle contractions and standard deviation are the parameters generated by the software for each trial and for each participant. As a measure of variability of FR we accepted the coefficient of variation (*CV* [%]), defined as the mean force generated divided by *SD* and multiplied by 100%.

Statistical analysis

Statistica 10 (StatSoft, Cracow, Poland) was used for statistical analysis. Data normality was confirmed by the Shapiro-Wilk's test. Because the variances are different for each load in both sex groups, the nonparametric Kruskal-Wallis test on ranks was used for intragroup comparison. Differences between men and women were compared with the Student's unpaired *t*-test. The confidence interval for the presented results is above 95%. The level of statistical significance was set at 5% ($p < 0.05$).

Results

Isometric maximum voluntary contraction

Across all maximum forces contraction F_{max} [N] measurements, females were weaker than males (Table 1).

As for maximal forces, LEE performed with the targeted force of 98 N constituted 70% of the maximal force in females, which corresponded with 147 N in males. Forces triggered during elbow flexions represent similar percentage of maximal values in both sexes: 25 ± 2% for 49 N, 45 ± 4% for 98 N, and 70 ± 5% for 147 N. With regard to F_{max}, the Student's unpaired *t*-test between groups (F/M) showed a statistically significant difference only for LEF; the *CV* values corresponded with the 45% of F_{max} (F, 98 N vs. M, 98 N, LEF $p < 0.02$) (Figure 2). We did not compare results for lower limbs as the % of F_{max} was different for both sexes on each level of the triggered force.

Isometric sub-maximal force repeatability

The analysis of isometric FR for females (Figure 3A) with an increase of predetermined force showed a significant decline of variation in repeatedly generated forces for elbow extension and flexion contractions, when comparing the target of 49 N vs. 98 N and 49 N vs. 147 N. The FR increased significantly in RKE between 49 N and 147 N, and in LKE between 49 N and 98 N (in both cases, $p < 0.000$) (Figure 4). There were no significant differences between 98 N and 147 N in both elbow or knee movements.

In the male group (Figure 3B), we did not notice any changes in FR with the target force increases for REE.

Table 1. Maximum force values (mean ± *SD*) for females (F) and males (M), and the level of significance (*p*-value)

	F	M	*p*-value
REF	218 ± 23	229 ± 23	< 0.28
LEF	202 ± 39	245 ± 53	< 0.005*
REE	140 ± 32	206 ± 20	< 0.001*
LEE	145 ± 36	192 ± 15	< 0.001*
RKE	199 ± 49	264 ± 64	< 0.001*
LKE	219 ± 50	238 ± 60	< 0.32

REF – right elbow flexion, LEF – left elbow flexion,
REE – right elbow extension, LEE – left elbow extension,
RKE – right knee extension, LKE – left knee extension
* statistical significance

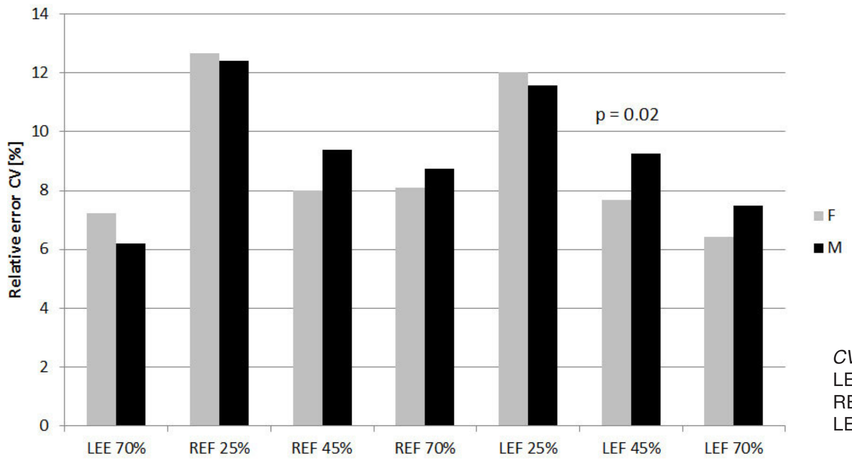
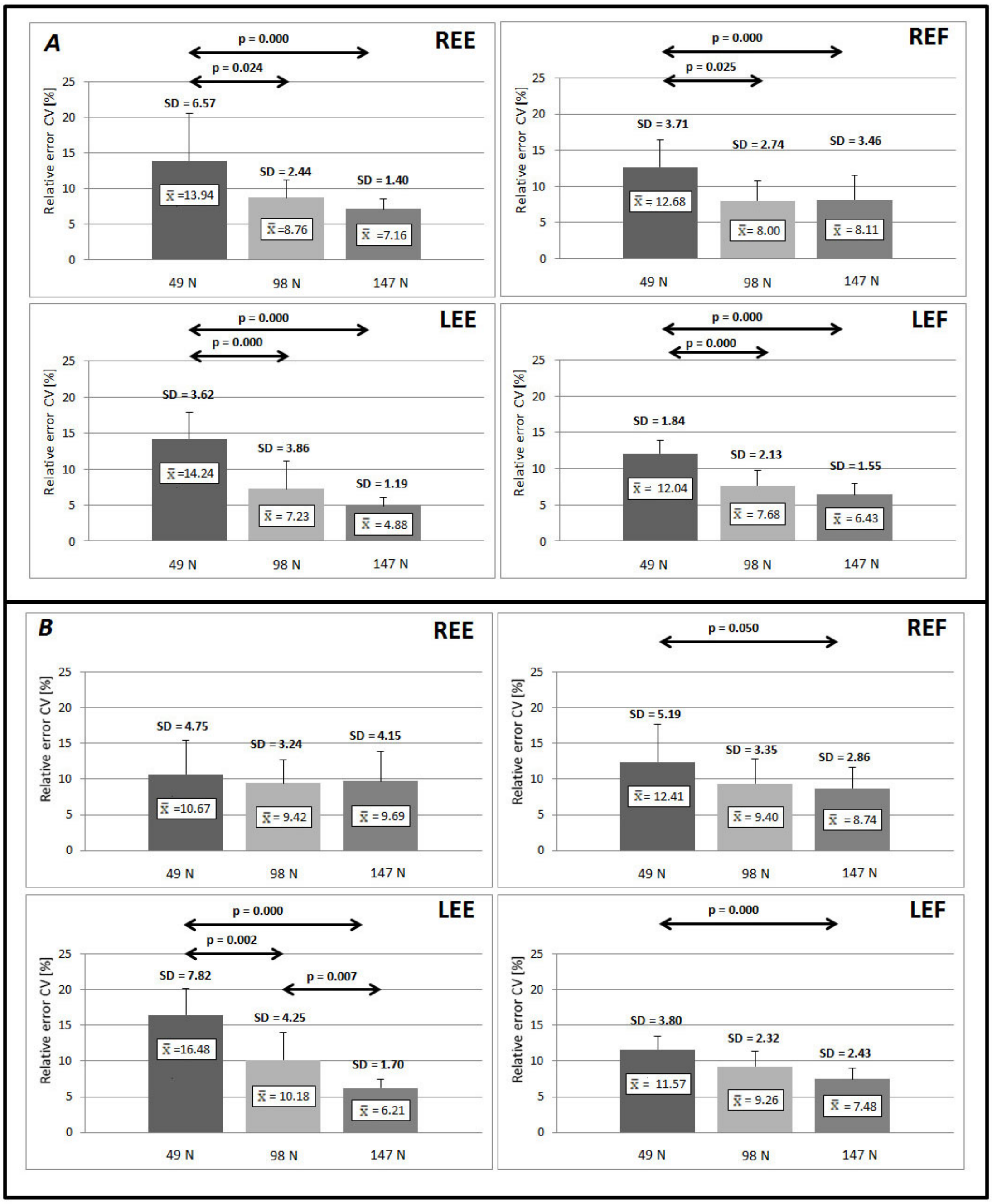


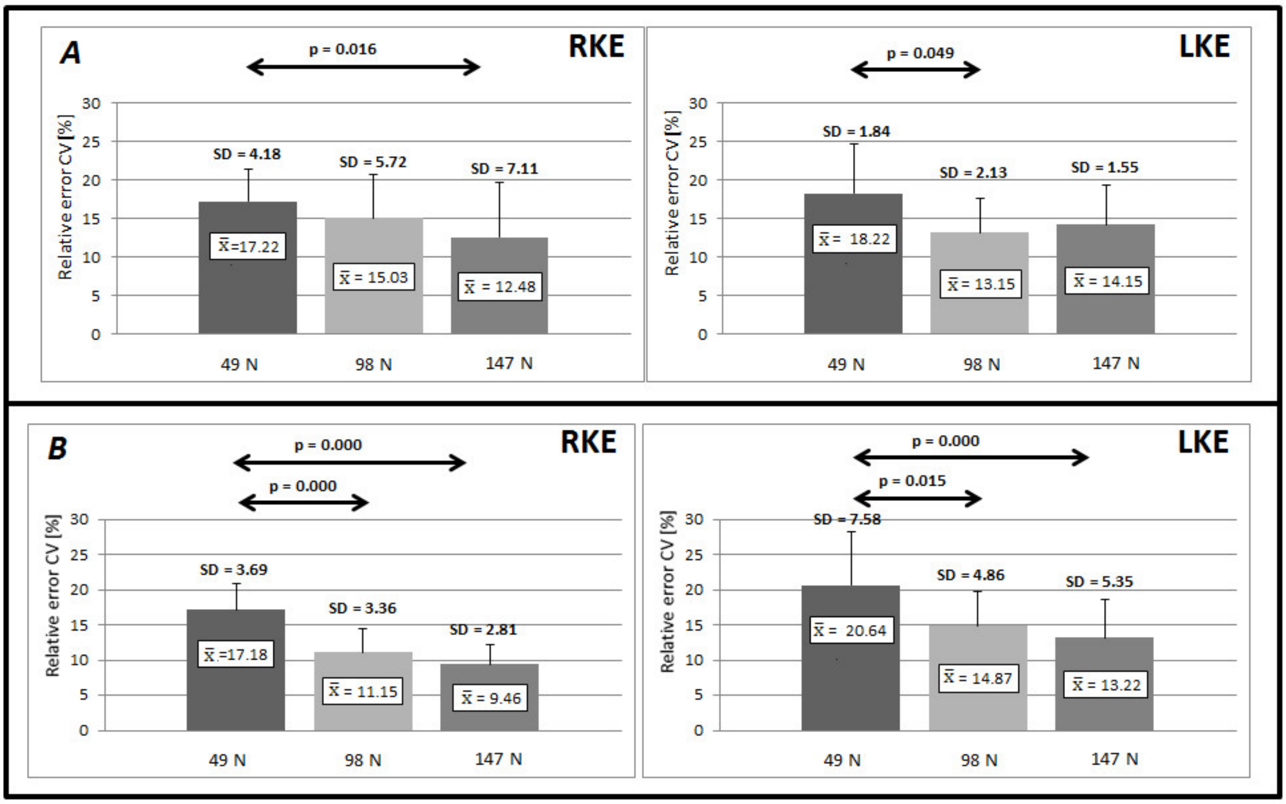
Figure 2. Gender differences in sub-maximal forces in relation to F_{max}

CV – coefficient of variation
LEE – left elbow extension
REF – right elbow flexion
LEF – left elbow flexion



CV – coefficient of variation
REE – right elbow extension
REF – right elbow flexion
LEE – left elbow extension
LEF – left elbow extension

Figure 3. Difference in sub-maximal forces for elbow movements in females (A) and males (B)



CV – coefficient of variation, RKE – right knee extension, LKE – left knee extension

Figure 4. Difference in sub-maximal forces for knee extension movements in females (A) and males (B)

As opposed to REE, the variation of FR by left arm in elbow extension showed a significant decline in each comparison (49 N vs. 98 N, 49 N vs. 147 N, 98 N vs. 147 N). For elbow flexion, the differences were only observed between the extreme measurements (49 N vs. 147 N).

In males, the accuracy in FR rose with increase of force target from 49 N to 98 N and 147 N ($p < 0.001$) (Figure 4).

Significant gender differences (F/M) in relation to the force targets were observed in *CV* mainly for elbow extension contractions: REE on 49 N ($p < 0.01$) and 147 N ($p < 0.05$), LEE on 98 N ($p < 0.01$) and 147 N ($p < 0.01$); and RKE on 98 N ($p < 0.01$).

Discussion

In this study, we tested whether the force value and sex influenced the accuracy of FR in relation to muscle function with three different target forces. It was found out that use of several target forces to assess force sensation by the repeatability of the force generated by upper and lower limbs had a similar influence on the value of the *CV* in men and women. In both sexes, the accuracy of force generation increases accordingly to the rise of the target force. In women, the most visible changes were noted between 49 N and 98 N, and between 49 N and 147 N (Figure 3A), in men between 49 N and 147 N (Figure 3B).

Our finding that females are weaker than males is consistent with other studies that investigated sex differences in strength [1, 11, 17]. There are, however, some inconsistencies. Our results show that women were approximately 68% for REE and 75% for LEE, 95% and 82% for REF and LEF, respectively, and 75% and 91% for RKE and LKE, respectively, as strong as men. Miller et al. [11] reported the maximal forces exhibited by sedentary women on the level of 52% and 66% of forces exhibited by sedentary men for elbow flexors and knee extensors, respectively. Christine [17] observed that the muscle strength in females equalled 2/3 of that in males, indicating that these differences may arise from various daily life physical activity levels. We assume that the smaller gender differences obtained in our search may be explained by the level of the participants' physical activity. Although they were untrained individuals, both groups were students of physical education faculty and their performance and strength level may be higher than in sedentary subjects. The robust adaptive property of skeletal muscles, especially at the beginning of chronic muscular work, may influence the adaptive changes in female muscles more profoundly than in males. Substantial changes in level of daily physical activity in females may have led to a greater shift in their muscle strength. This is the only explanation considering that chronic muscular work results in an increase in the muscle contractile proteins and fibre area [18].

Although there is strong evidence for variance within males and females in strength, in order to accurately assess the role of sex in force sensation, we decided to express the chosen loads as a percentage of maximal force (Figure 2) and in term of absolute targeted forces. Independently of force-exerted value, both sexes were characterized by similar levels of FR in elbow flexion (Figure 2). In this aspect, our data are consistent with the results of Svendsen and Madeleine [7], whose subjects were to perform 9 contractions ranging from 10% to 90% of maximal voluntary contraction (MVC), with 10% increments in between. However, they differed from one another in the level of variation at the lowest triggered force (25% of MVC), which might result from aim and protocol differences. The study of Svendsen and Madeleine [7] were focused on force variability during the elbow flexor contractions with different time and force levels and with visual feedback. Our study was concentrated on FR variation during a series of 10 rapid contractions and restoring the forces on the basis of a memorized pattern without visual feedback. The significant drop in FR variation for elbow flexion (EF) in females and at the margin of significance in males ($p < 0.06$) between 49 N and 98 N, as well as lack of such change between 98 N and 147 N may suggest that the variability in repeated force production decreases exponentially between 25% and 45% of F_{max} and is nonproportional to a higher force level [7, 19]. The simplest explanation would be that with an increase of triggered force, there is a parallel increase in proprioceptor stimulation, which in turn affects the generated forces repeatability. Although there is strong evidence that the lack of peripheral perception does not disturb the ability of exertion of targeted forces [20], we suggest that proprioception importance is increased in parallel with a rise in muscle mass engaged during contraction.

The only gender difference in relation to F_{max} that we noticed was for LEF performed with 45% of F_{max}, which was equal to 98 N in both sexes (Figure 2), and the females were more accurate. Females also generated contractions more accurate than males during REF 45% and 70%, and LEF 70%, but sex differences in those cases are off significance. These differences might be attributed to sex differences in muscle size [3], muscle structure [10, 11], or the adaptive changes in muscles, arising from gender difference in everyday tasks, which can affect the neural drive – mainly on the level of synaptic circuitry organization in the spinal cord [21] – but have little impact on the motor cortex organization [22].

There is no doubt that a bigger muscle cross-sectional area results in greater muscle force in men [9]. There are also studies pointing sex differences in the section area of fast (FT) and slow (ST) twitch muscle fibres [10, 11]. In women, a larger cross-section was observed in ST muscle fibres compared with FT muscle fibres IIA and IIB, and in men, conversely. Additionally, differences in the section area of ST and FT muscle fibres [10, 11] might be a factor responsible for the observed discrepancies between males and females. These differences in muscle structure between males and females may in turn lead to lower maximal force in females and smaller precision in the generated FR in males. Gender differences appeared by an increase of predetermined force and in the comparison of REE with 49 N ($p < 0.05$), LEE with 98 N ($p < 0.05$) and 147 N ($p < 0.01$), and RKE with 98 N ($p < 0.01$). It is known that greater force requires the involvement of a bigger number of motor units. In females, where the muscle composition is shifted towards the slow fibres [11], there is greater involvement of ST fibres with force increases, whereas in males, where the muscle contains more FT fibres, an increase in force raises their involvement. It may be assumed, as the ST fibres form small motor units, that an increase of triggered force may cause fewer errors during repeated force generations. In men, where the fast motor units dominate, a smaller improvement in FR with a shift of target was noticed. Our results might indicate that the way in which muscle tension is regulated by the central nervous system does not differ between the sexes [23] and the observed variations are a result of the diversity in the body and muscle structures [9, 11].

Independently of the level of maximal forces exerted in both females and males, the error values achieved during targeted force production are similar: 12–14% for 49 N, and 6.5–8.5% for 98 N and 147 N in females, as well as 11.5–16% for 49 N, 9–10% for 98 N, and 6–9% for 147 N in males (Figures 3 and 4). It may suggest that isometric force sensation during uncontrolled force exertion (without vision control) is similar in both sexes. The neural excitation, strategy of muscle fibre engagement, independently of the sex, causes the appearance of similar error magnitude during the liberation of forces.

The research performed by Sainburg [24] shows that in right-handed people, the dominant system of the right limb and left hemisphere specializes mainly in the control of movement dynamics, while the system of the left limb and right hemisphere is responsible, most of all, for the control of the static position of the limb. In our experiment, participants were obligated to generate 10 times the targeted force on each level without visual feedback and to adapt the position before each force generation. We noticed a regular decrease of *CV* [%] in LEE in both sexes, occurring simultaneously with an increase of triggered force and between the exerted forces of 49 N vs. 98 N and 147 N (Figure 3A) in females and between each measurement in males ($p < 0.001$) (Figure 3B). We also observed that in both groups the errors in force production by the right arm were greater than those for the left arm, and in the case of the target force of 147 N the difference was significant ($p < 0.005$) (Figure 3). Kubota and Demura [25] found that in maximal handgrip strength of the dominant and non-dominant hands there were gender variations. Our data show laterality for elbow flexion and extension, with lower variation in force production by the left (non-dominant) arm (except REE vs. LEE with 49 N and 98 N in males), although without gender impact. Wang and Sainburg [26] reported that the non-dominant limb made a better use of the feedback information from proprioceptors. By contrast, Baraldi et al. [27] proved that the dominant right hand used larger cortical representation than the non-dominant left hand, which is a result of, among others, cortical plasticity. As the *CV* decreases with a shift of target force and becomes significant with 147 N, we can speculate that feedback information (both from proprioceptors and tactile receptors) in the non-dominant hand plays a crucial role in proper high-level force generation. Additionally, the left hand, controlled by the right hemisphere, is responsible for the precise exhibition of the force indispensable to holding an item being an object of precise manipulation by the right limb – the dominant one [28]. Taking this into consideration, the noticed that asymmetry in FR might be a result of laterality and the ensuing adaptive changes bound with everyday tasks.

Conclusions

As a conclusion, it can be stated that the value of the generated force influences its repeatability, although there are no gender differences in FR during knee extension and elbow flexion. The asymmetry in FR that was revealed in subjects of both genders may result from laterality and the ensuing adaptive changes bound with everyday tasks. The lack of significant differences in FR between elbow flexion and extension shows that the central nervous system similarly regulates sub-maximal contractions of the elbow flexor and extensor. The neural excitation, strategy of muscle fibre engagement, independently of the sex, causes the appearance of similar error magnitude during the liberation of sub-maximal forces.

Acknowledgements
The authors wish to thank all the volunteers who participated in the study.

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