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Evaluation of Age and Sex Effects on Force Complexity and Fluctuation during isometric elbow flexion

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Abstract—This study attempts to examine the impact of age and gender on fluctuations in force output during voluntary muscle contractions and how this impacts task performance. More precisely, the study investigates how these fluctuations vary during an elbow flexion task at sub-maximal forces. Interestingly, the study found that elderly women exhibit lower steadiness, meaning they exhibit a diminished capacity to maintain a steady force output and lower complexity than young adults when dealing with high levels of contraction. This suggests that women may have a diminished ability to maintain a steady and adaptable force output during the elbow flexion task, which could affect their performance. However, the findings from this study show that the existence of notable differences in force fluctuations among diverse age groups was limited to specific levels of contraction. Thus, it can be deduced that various factors, apart from age alone, might contribute to the observed decrease in force fluctuations in this study. Additionally, there are differences in behavior between women and men.

Index Terms—aging, force, steadiness, complexity, muscle, elbow flexion

I. INTRODUCTION

Age-related changes in motor units significantly impact both strength and force control, resulting in a reduction to generate accurate levels of force [1]. Age-related changes involve various aspects related to motor units and motor neuron function such as a loss of motor units, alterations in discharge rates, motor unit remodeling, or variations in the common synaptic input to motor neurons.. [1], [2]. [1], [2]. These changes provoke a decline in their maximal force, which refers to their strength, and a decline in their ability to control their movements and perform tasks with precision, which is known as force control and task performance [3], [4]. However, Some studies suggest, that as individuals begin to age, the initial stages of decline in functional capacity appear to be more connected to difficulties in controlling force rather than a decrease in the ability to generate maximum force. [5]. Studies have shown that there are

disparities in both the magnitude of force variations and force complexity between older and younger adults [6] [7] [8]. These changes contribute to the decline in older adults' capacity to engage in activities of daily living (ADLs) such as maintaining balance, moving about, and handling objects [9]. In addition to age-related changes in force control, sex differences in strength and force fluctuations have also been studied. Typically, men exhibit greater strength than women, which may contribute to differences in force control between genders [3].

Indeed, this study aimed to examine whether age-related changes in force fluctuations also extend to changes in the temporal structure or complexity of force signals during isometric elbow flexion and whether sex differences play a role in these changes. In particular, we quantified force fluctuations and complexity at 20%, 40%, and 60% of maximal voluntary contraction (MVC) in both young, middle-aged, and older men and women. This study is innovative as it explores potential disparities of the variations in stability and complexity of force signals among men and women, across three different age groups (**Young, Middle-aged, and Elderly**).

II. MATERIAL AND METHODS

A. Cohort description

The INSEAD Institutional Review Board has approved the study, and the data collection has been done at the INSEAD-Sorbonne University Behavioural Lab (protocol ID 2022-55) to assess age-related changes in muscle during elbow flexion. The cohort was built following specific inclusion criteria such as age, sex, physical activity (IPAQ), and healthy status.

Table I presents the participant characteristics, including the age (years) and BMI (kg/m²), for each age group and gender. The abbreviations used for the age groups are as follows: YM (Young Men),

YW (Young Women), MM (Middle-Aged Men), MW (Middle-Aged Women), EM (Elderly Men), and EW (Elderly Women).

TABLE I
PARTICIPANT CHARACTERISTICS (MEAN \pm STANDARD DEVIATION)

Age group	n	Age (years)	BMI (kg/m ²)
YM	9	23.2 \pm 4.35	21.9 \pm 2.1
YW	11	22.73 \pm 7.2	22.2 \pm 1.8
MM	11	46.9 \pm 5.6	23.8 \pm 2
MW	9	49.7 \pm 5.9	21.82 \pm 2
EM	10	69.9 \pm 6	23.8 \pm 2.1
EW	8	69.8 \pm 6.1	21.8 \pm 2.7

B. Force recording

A hand-made ergometer with a torque sensor (Model TFF350) was used to measure the elbow flexion of each participant. The participants were placed on a chair, and their upper arm was supported by the ergometer. Both shoulder and elbow were flexed at a 90° angle, with their wrist resting against a bar. They were instructed to perform isometric elbow flexion (Figure 1). The signals acquired from the torque sensor were amplified and displayed on a biofeedback screen, which provided the subjects with real-time information about their force production. The force values were digitized at a high sampling frequency of 2 kHz to allow precise complexity and deviation assessment. Simultaneously, HD-sEMG signals were also recorded but not exploited in this study.

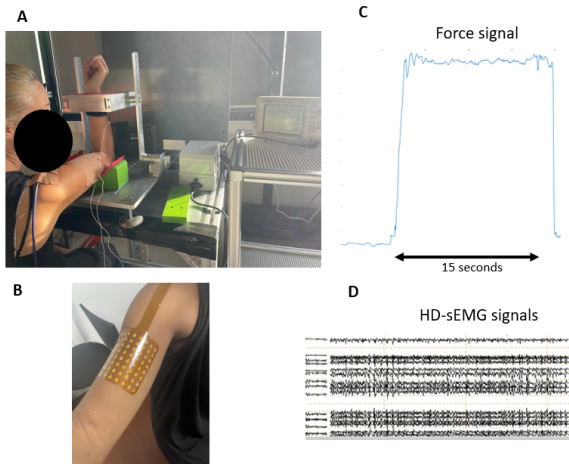


Fig. 1. A. Participant performing an elbow flexion exercise using the ergometer B. 64 electrodes grid placed on the BB muscle C. Force signal output D. HD-sEMG signals output

C. Experimental protocol

In the experiment, each participant was asked to perform three MVCs. The reference MVC was established as the highest of the three measurements, with a 5-minute interval between each measurement. After the MVC measurement, the subjects were given a 10-minute rest period. Subsequently, the participants

performed nine voluntary contractions, each lasting 15 seconds, at varying levels: three at 40% of their maximum capacity, three at 60%, and three at 20%. Even with the same order, no skill acquisition was observed among subjects. They were asked to maintain the asked torque level with fluctuations of no more than \pm 5% with visual biofeedback display.

D. Data analysis

A low-pass Butterworth filter of 4th order was applied with a cutoff frequency of 10 Hz [13]. This helped to eliminate high-frequency noise and artifacts that could potentially interfere with the analysis of the force signals. The resulting filtered signal is then suitable for further processing and analysis.

In the study, the analysis was specifically focused on the plateau phase of the constant-force trial, which lasted for 8-10 seconds for all target forces. To avoid any adaptability effects, the first 5 seconds of the signal were excluded, and only the following 10 seconds were analyzed. The exclusion of the initial 5 seconds helped to focus on a more stable and representative part of the signal, thus improving the accuracy and reliability of the results.

Moreover, the study observed no significant differences in fluctuations among the three trials. As a result, to minimize bias and ensure reliability, the values from the three trials were averaged to obtain a more robust and accurate estimate of steadiness values.

In the context of sustaining a constant force during a submaximal isometric contraction, the applied force is not constant, but, it fluctuates around a mean value. The method used to determine this steadiness of force during a muscle contraction is to calculate the coefficient of variation (CV) of force. This involves measuring the amplitude variability of the force produced during a constant-force contraction and expressing it as a percentage of the mean force [5]. To calculate the CV, the standard deviation of the force is divided by the mean force and then multiplied by 100%. A lower CV indicates greater steadiness of force production, while a higher CV indicates lower steadiness of force production [3].

Muscle force complexity can be defined as the variability and unpredictability of the forces produced by muscle contractions over time. Approximate entropy (ApE) is a used metric to evaluate the regularity of time series data such as muscle force [10]. ApE quantifies the likelihood that a given pattern of force fluctuations will repeat itself over time. Lower values of ApE indicate greater regularity and higher values indicate greater complexity [10]. ApE quantifies the negative natural logarithm of the conditional probability that a template is repeated during a time series.

The ApE formula :

$$ApE(m, r, N) = -\frac{1}{N-m} \sum_{i=1}^{N-m} \log \left(\frac{A_i}{B_i} \right)$$

Denoted as $ApE(m, r, N)$, operates by analyzing sequences of m data points to determine the logarithmic likelihood of these sequences resembling other sequences within the dataset. Matching templates, which maintain their similarity within a defined tolerance ' r ', are identified and quantified. The count of matches to the ' i -th' template, which has a length of ' m ' data points, is denoted as ' Bi '. Following this, the algorithm proceeds to count the instances where these matches persist even when considering the ' $m \pm i$ -th' data point. This count is represented as ' Ai ' for the ' i -th' template. In the context of sequence comparison, sequences are deemed similar only if the difference between them exceeds the specified noise threshold r [10]. Indeed, ApE was computed for each one-second epoch for all signals using this method by fixing $m=2$ and $r = 0.25$.

E. Statistical analysis

The force measurement between gender groups was compared using Welch's t-test. The force measurements between different age groups were compared using an analysis of variance (ANOVA) with age group as a between-subjects factor. Pairwise comparisons between the age groups were conducted using Tukey's honest significance test to establish if there were significant differences in force measurements between any of the groups.

The statistical analysis was performed using the Matlab software (Version: 9.13.0 (R2022b)) in this study. A significance level of 0.05 was used for all statistical tests, and the results are presented as the mean \pm standard deviation (SD) in the text. The figures' values are displayed as the mean \pm standard error of the mean (SEM) to provide a clearer representation of the data. The SEM is equal to the ratio of the standard deviation to the root of the sample size.

III. RESULTS

A. Maximum voluntary contraction

Table II presents the mean and standard deviation of torque for each age group and gender.

In terms of the MVC of the elbow flexors among the men group, no significant differences were observed ($P > 0.05$). However, for women, the ANOVA test revealed significant differences between the age groups. To further investigate these differences, pairwise comparisons were conducted. It was found that the MVC was significantly greater in younger women compared to elderly women ($p = 0.0068$). However, there were no significant differences in MVC between young and middle-aged women ($p = 0.051$), as well as between middle-aged women and elderly women ($p = 0.34$). The results indicate that the MVC values were significantly lower in women compared to men ($P > 0.05$) for the middle-aged group and ($P > 0.01$) for the young and elderly groups (Table II).

TABLE II
MEAN AND STANDARD DEVIATION OF TORQUE FOR EACH PARTICIPANT WHERE "N.S." DENOTES "NON-SIGNIFICANT" (NULL HYPOTHESIS REJECTED), "*" DENOTES A P-VALUE OF 0.05; "*" "*" DENOTES A P-VALUE OF 0.01, AND A P-VALUE OF 0.001

Age group	Torque (Nm)
YW	37.5 \pm 9.2**
MW	34.9 \pm 7.3
OW	25.3 \pm 6.7
YM	61.5 \pm 15.3
MM	51.9 \pm 10.6
OM	50 \pm 9.7

B. Coefficient of variation

Figure 2 displays the coefficient of variation (CV) and standard error of the mean at different levels of MVC for each age group and gender.

Age Differences

The force steadiness was significantly greater ($P < 0.05$) in the elderly age group at 40% MVC than young men and middle-aged group for men and 60% for women group. The CV of young women (2.65 ± 1.47) was significantly greater ($P < 0.05$) than middle-aged women (1.52 ± 0.78) and (1.12 ± 0.83) in Elderly women (Figure 2). For men, a similar observation was made, but the difference did not have statistical significance. with a P -value of less than 0.5.

Sex Differences

The coefficient of variation (CV) values reflect the variability in force steadiness. Significant differences between sexes are observed at different force levels. Specifically, at 40% and 60% of maximal voluntary contraction (MVC), the CV is significantly higher in women compared to men ($P < 0.01$). On the other hand, at 20% MVC, men exhibit a significantly higher CV compared to women ($P < 0.01$). This indicates that there are distinct sex differences in force steadiness, with women generally displaying greater variability at higher force levels and men exhibiting higher variability at lower force levels.

C. Approximate entropy

Figure 3 displays the approximate entropy and standard deviation for each age group and sex at different levels of MVC.

Age Differences

Although a decrease in complexity was observed with age in the men's group at 20% and 40% MVC, the difference in approximate entropy was not statistically significant. This suggests that factors other than age may contribute to the decline of complexity in force movements during elbow flexion for men at those specific levels of MVC.

Sex Differences

At 40% and 60% MVC, Figure 3 shows that men exhibited higher approximate entropy compared to women in all age groups. However, at 20% MVC, the differences in approximate entropy between men and women were not statistically significant. These results indicate that the sex differences in complexity during elbow flexion, as indicated by approximate entropy, may be influenced by the level of muscle contraction.

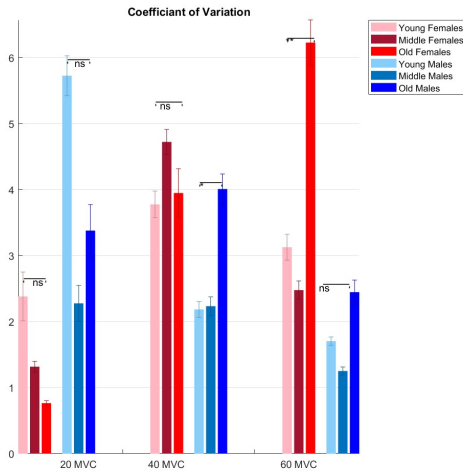


Fig. 2. Mean \pm SEM of coefficient of variation for each age group

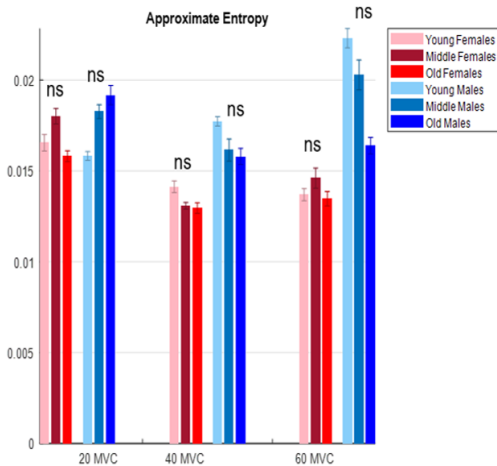


Fig. 3. Mean \pm SEM of approximate entropy for each age group

IV. DISCUSSION AND PERSPECTIVES

In agreement with the literature, this study found that women had a lower maximal voluntary contraction (MVC) of elbow flexors compared to men, indicating a sex discrepancy. The study also noted that at 40%

and 60% MVC, men exhibited greater steadiness and lower variability than women did. This finding may be explained by the difference in maximal torque between men and women, a higher MVC than women, which can cause more force stability and less force variation in muscle activation levels during these levels of contraction [12] [3].

However, concerning age differences, the MVC of elbow flexors only differed significantly between younger and older women. Furthermore, there were only significant differences in force steadiness at 40% for men and 60% for women. Although it has not been found a statistically significant decrease in signal complexity in older men during voluntary muscle contractions at 20% and 40% of MVC. The observed trend towards decreased complexity, especially at 60% of MVC, may suggest a decline in adaptability and control of force output. Several studies have also consistently reported a lack of significant differences in force steadiness among the muscles responsible for elbow flexion [9]. However, the complexity, for all the studied contraction levels, seems to be higher for men than women. Future research should focus on tasks involving fine motor skills and consider lifestyle factors like physical activity level and occupation, which can affect muscle force variability and contribute to age-related changes in force control [3]. The impact of age on force control may vary across different muscle groups, with some showing significant changes while others may not [6] [7] [9].

Moreover, it is important to acknowledge sex disparities in age-related changes, with women potentially experiencing different or greater declines in force control for elbow flexor muscles due to factors such as reduced engagement in activities that utilize specific muscle groups [12] [11]. Recent research has demonstrated a sex-specific degradation of the neuromuscular system, with women being more susceptible to such degradation, largely influenced by hormonal differences [12].

V. CONCLUSION

This study attempted to examine the impact of age on force steadiness and complexity during elbow flexion at various levels of contraction (ranging from 20% to 60% of maximal voluntary contraction). The results revealed that women show lower force steadiness and increased complexity compared to men. Regarding age differences, significant variations were observed only for specific levels of contractions. This study confirms the importance of considering factors such as sex disparities, the specific muscle group involved, and the level of contraction when examining force fluctuations and complexity. However, further studies with larger cohorts are needed to confirm the obtained results.

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