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Research Paper

Force control of pinch grip: Normative data of a holistic evaluation

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A B S T R A C T

Background: Pulp pinch (PP) is a vital hand movement involving muscle strength and sensory integration. Previous research has primarily focused on Maximal Voluntary Contraction, but PP encompasses broader parameters.
Purpose: This study aims to establish normative data for a comprehensive evaluation of thumb and index force control during PP, including endurance, precision, accuracy in unilateral PP, and force coordination in bilateral PP.
Study Design: A cross-sectional study.
Methods: Three hundred and twenty eight healthy Italian cis-gender participants (169 females, 159 males) were enrolled in a multiparametric force control evaluation of pinch grip, consisting in: sustained contraction (SC: ability to maintain a stable contraction at 40% MVC, measured as the time until exhaustion), dynamic contraction (DC: the ability to modulate precisely and accurately force output to follow a dynamic force trace), bimanual strength coordination (BSC: the ability to coordinate in-phase bimanual forces at different combined magnitudes) tasks. The sample was divided per sex and stratified in five age groups taking into account hand dominance. Differences in tasks' results between age, sex and hand-dominance were analysed.
Results: Endurance (SC) was similar between younger and older adults ($\eta^2 = 0.047$ (Females) and $\eta^2 < 0.007$ (Males)). Older adults exhibited lower precision (DC) and coordination (BSC) compared to young adults in both sexes ($\eta^2 > 0.16$). Females demonstrated greater endurance (SC) but lower precision and coordination (BSC) compared to males ($0.01 < \eta^2 < 0.1$). No hand dominance effect emerged in SC and DC.
Conclusions: Force accuracy and precision to modulate pinch force to perform a visual feedback force-matching task (DC) and force coordination between hands (BSC) worsen at increasing age. Hand dominance did not influence either endurance or precision of pinch grip in visual-feedback guided task.

Introduction

Pulp pinch (PP) is a fundamental movement to perform different activities of daily life.[1,2] PP is influenced by muscle strength and the integration of sensory input and central processes that develop the right force output while coordinating the fingers and hands.[3] Previous research has predominantly focussed on the study of PP Maximal Voluntary Contraction (PP-MVC).[4,5] PP-MVC is an objective outcome, with high test-retest reliability,[6] commonly used in hand injuries to test treatment effectiveness and monitor the progress of recovery.[7,8]

However, PP is considered as a precision rather than a power grip, as it is used to manipulate small objects at various submaximal contractions also for a long time.[9] Consequently, PP-MVC alone cannot adequately represent the multifaceted aspect of hand function. For example, PP-MVC showed just a low correlation with hand dexterity[10] and pinch strength control.[11] Thus, there is a need for a more comprehensive, holistic evaluation of PP. This evaluation could consider a combination of various tests to evaluate different factors of hand function.

For instance, endurance tests are recognized to be useful for the evaluation of several musculoskeletal disorders[12,13] and diseases where fatigue represents a major symptom[14] across various anatomical regions. Considering the prevalence of sustained pinch grip in many occupational activities (such as periodontal scaling, tailoring, embroidering, carpet weaving),[15–17] endurance tests could provide important clinical information related to hand motor control and functionality.

Furthermore, the accuracy, precision, and variability in the application of force are essential characteristics for manual motor control, particularly during the execution of fine digital movements

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or in the manipulation of small object.[18] Thus, assessing these variables during PP grip through specific force target-matching tests, could reveal valuable insights into manual dexterity and how it is impacted by age-related or pathological conditions.[11,19]

Finally, PP is usually used in bimanual tasks. Therefore, the ability to produce pinch forces at different magnitudes with both hands simultaneously could represent an interesting outcome in the evaluation of interlimb force coordination in neurological diseases.[20]

Moreover, considering the previous literature that explored how age-related factors influence endurance across different body districts, it is reasonable to expect a preservation or an increase of endurance capabilities,[21] despite a potential decline in precision and coordination variables.[22,23] Furthermore, regarding sex differences, prevailing trends suggest that females may exhibit superior endurance capacities.[24] Conversely, males may demonstrate better precision and coordination.[25,26]

Regarding possible discrepancies between the dominant and non-dominant hand, no differences in endurance[27] and in precision[28] were found in the literature.

Based on the above considerations, the present study aims to establish normative data of a holistic evaluation of thumb and index force control during PP stratified by age and assigned sex (at birth) in a population of people without specific diseases, highlighting differences between sex and age groups. This evaluation will encompass aspects of endurance, force precision, and accuracy of the PP, during a unilateral pinch-and-release task, as well as force coordination between hands during a simultaneous bilateral pinch-and-release task.

Materials and methods

Study design

A cross-sectional design study was developed to establish normative data of a new holistic evaluation of thumb and index force control in PP position. This evaluation consisted of performing three different tests: sustained contraction (SC), dynamic contraction (DC), and bimanual strength coordination (BSC). This study is reported according to Strengthening the Reporting of Observational Studies in Epidemiology (STROBE)[29] and the Sex and Gender Equity in Research (SAGER)[30] guidelines. This study was conducted following the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee for University Research (CERA: Comitato Etico per la Ricerca di Ateneo), University of Genoa (approval date: 10/06/2020; CERA2020.06).

Experimental equipment

For the experimental session, a visual feedback-based pinch meter (EMAC s.r.l., Genova, Italy) was adopted (Fig. 1). This pinch meter consisted of two force cells, connected to an amplifier to convert the signal from analogical to digital. The output signal was sent to the PC via USB and analysed by the proprietary software which had the function of guiding participants and assessor over the tests, through a friendly graphical user interface (GUI).[31]

Experimental session

All participants undersigned an informed consent for privacy, participation and data treatment before entering the study. The experimental sessions were conducted by a single assessor, a physiotherapist previously trained in the use of the abovementioned pinch meter and related software. People's posture was standardized according to the American Society of Hand Therapists (ASHT) recommendations.[32] Briefly, the participant was seated in front of a table with forearms resting on it in a neutral position, wrist in a neutral position, and feet on the ground. A PC screen was positioned on the table at 85 cm from the participant (Fig. 2).

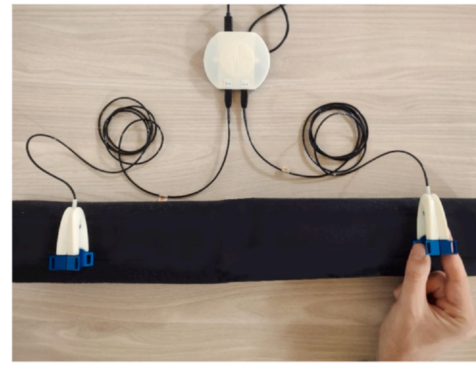

Fig. 1. Digital Pinch Meter adopted for this study.

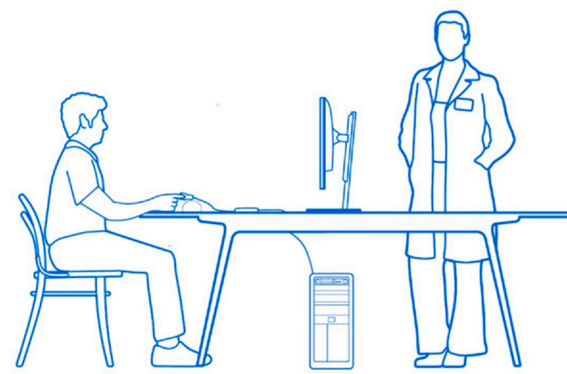

Fig. 2. Participants' posture during the assessment.

Each participant was instructed about the measurement system, the application and the posture they had to maintain during the experiment. For the PP configuration people had to take the force cells between thumb and index pads, keeping the fingers straight and parallel, the other fingers were clenched[33] since pinch strength is influenced by the position of both elbow, wrist, hand and fingers joints.[34,35] As a result, interphalangeal joints are extended, and the thumb is forced to be straight and parallel to the forearm so that the standardized position of the wrist is guaranteed.

Before performing the experimental protocol, participants had to undergo a familiarization trial with the devices to get them acquainted with the pressure area onto which the clenching movement of every task took place. The battery of tests proposed in this experimental protocol consisted of SC, DC and BSC which respectively investigate the ability to maintain stable force across time, the force control during a pinch-release task and the strength coordination between hands.

The unilateral tests (SC and DC) were conducted with both hands, sequentially. To limit the impact of fatigue on the scores, the order of tasks and hands was randomized by using the "RAND" function in Excel (Excel Software, Microsoft Corporation. 2018). Moreover, a one-minute break was taken after DC and BSC, and a three-minute break after SC. The difference in the time-break was chosen because of the higher fatigue produced by SC. Before starting the experimental session, the thumb-index PP MVCs of both hands were acquired. The participants had to perform the MVC task twice per hand and the highest values of which were collected to define the target levels for the tests.

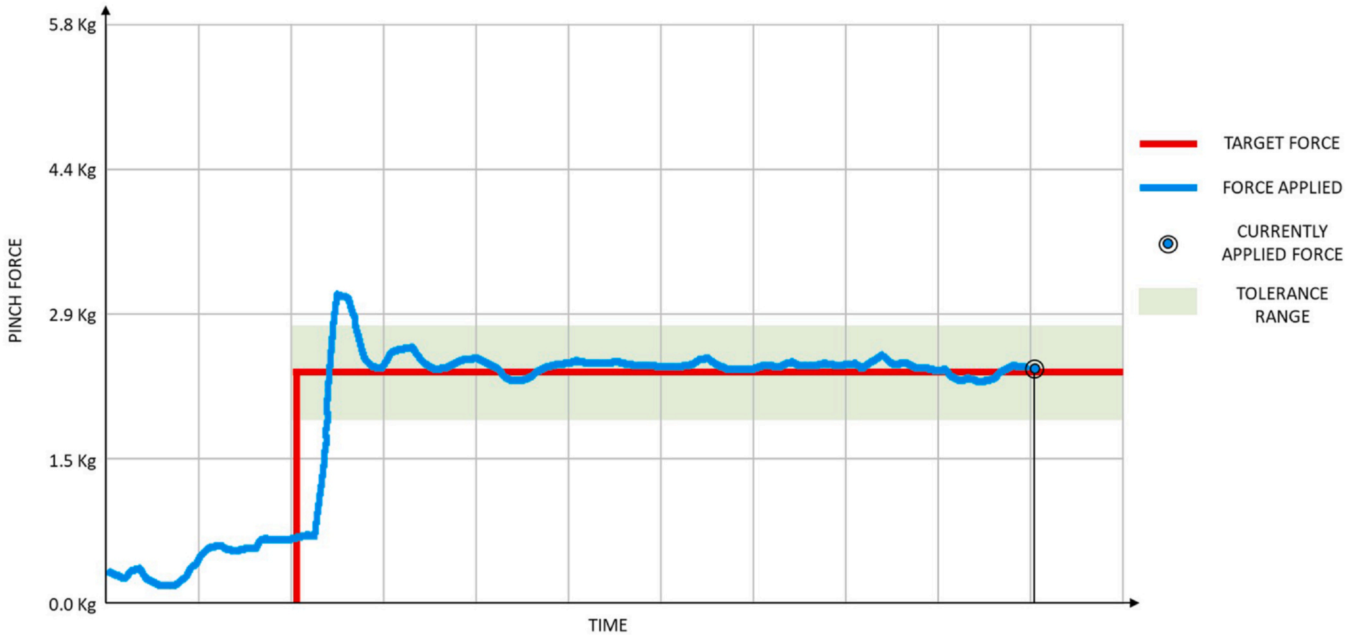

Fig. 3. Graphical representation of the sustained contraction (SC) test as seeing by the participants.

Sustained contraction

During the SC, participants had to reach and maintain a constant target force level set at 40% of PP-MVC (SC target force) until exhaustion. The target force was displayed on the monitor as a horizontal constant red line located at the middle of a tolerance range identified through two lines (± 10% of the SC target force). The force delivered by the participants was displayed as a blue line that raised according to the pressure exerted on the force cell. The task was automatically interrupted if the delivered force stayed below of 10% of the SC target-force line for longer than 1 second (Fig. 3).

Dynamic contraction

The DC consisted of a force-matching visual feedback-based test, in which the participants had to deliver a force in PP position to follow a target force that was graphically represented by a red square wave of four equal periods (Fig. 4). Each period was identified by an epoch lasting 3 seconds and a rest period of 3 seconds in which the target had been set at 0 kg. In the 4 epochs the targets were set at various %MVC levels (i.e., 70%, 40%, 25%, 10%) that were displayed on the monitor from the highest to the lowest. Even if a tolerance range was not displayed in this test, the participants had to stay as close as possible to the force target.

Bimanual strength coordination

The BSC test consisted of exertion of synchronous bimanual forces at different magnitudes,[36] using both force cells simultaneously (Fig. 5). The first step of this test required the construction of the “Range of Force” (RoF) polygon (Fig. 5A). The participants had to hold both devices in PP position and perform three tasks: left-hand (L-MVC), right-hand (R-MVC) and bilateral MVCs. The bilateral MVC consisted of performing the MVC task with both hands, simultaneously (Fig. 5B). The highest value between the two trials was recorded for each task. In a Cartesian system, R-MVC and L-MVC represented two points on the x- and y-axis, respectively. The third point was the sum of the force values contemporaneously recorded with the right and left sensors during the bilateral MVC. The three points and the origin of the Cartesian system constituted the vertices of the RoF polygon.

During the BSC test, 12 targets, graphically displayed as red points into the RoF polygon, randomly appeared in series, one after the other. They represented either symmetric or asymmetric combinations of strength (Left/Right %MVCs): 70/70, 40/40, 30/30, 20/20, 70/12, 40/9, 30/6, 20/4, 12/70, 9/40, 6/30, 4/20.[37,38] Around each target, a tolerance range of ± 10% MVC for each hand was graphically displayed as a light red oval. Each target and its associated tolerance range were displayed for 5 seconds. This period identified a single epoch. Each epoch was separated from the subsequent one by 3 seconds of resting period. The force exerted by each participant was displayed as a blue point cursor on the RoF polygon. By modulating the force of the index and thumb of both hands independently in PP position, the participants had to reach with the blue cursor each red point as quickly as possible and to keep it close to the target until its disappearance. As soon as the blue point enters the red oval (tolerance range of the target), the latter turns green in real-time.

Participants

Eligible participants had to be: over 18 years old, without any musculoskeletal, neurological, cardiovascular, metabolic disorder, acute pain or functional restriction that could impact upper limb strength. People unable to understand the tasks or with visual restrictions that could hinder the view of the computer monitor were not considered eligible. The use of spectacles or contact lenses was allowed. Mixed-handed participants were excluded.[39]

We employed a multi-stage sampling strategy to ensure representation from diverse demographic groups. Initially, we identified potential recruitment sites across various communities in Liguria, Lombardia and Piemonte (three Italian regions), including healthcare facilities, community centers (companies, offices, social centers) including workers with both high and low hands demand, and educational attainments (universities and high schools). At each site, all individuals who met the inclusion criteria were personally contacted and invited to take part in our study. They were informed of their autonomy in deciding whether to participate and were assured that they could withdraw from the study at any point.

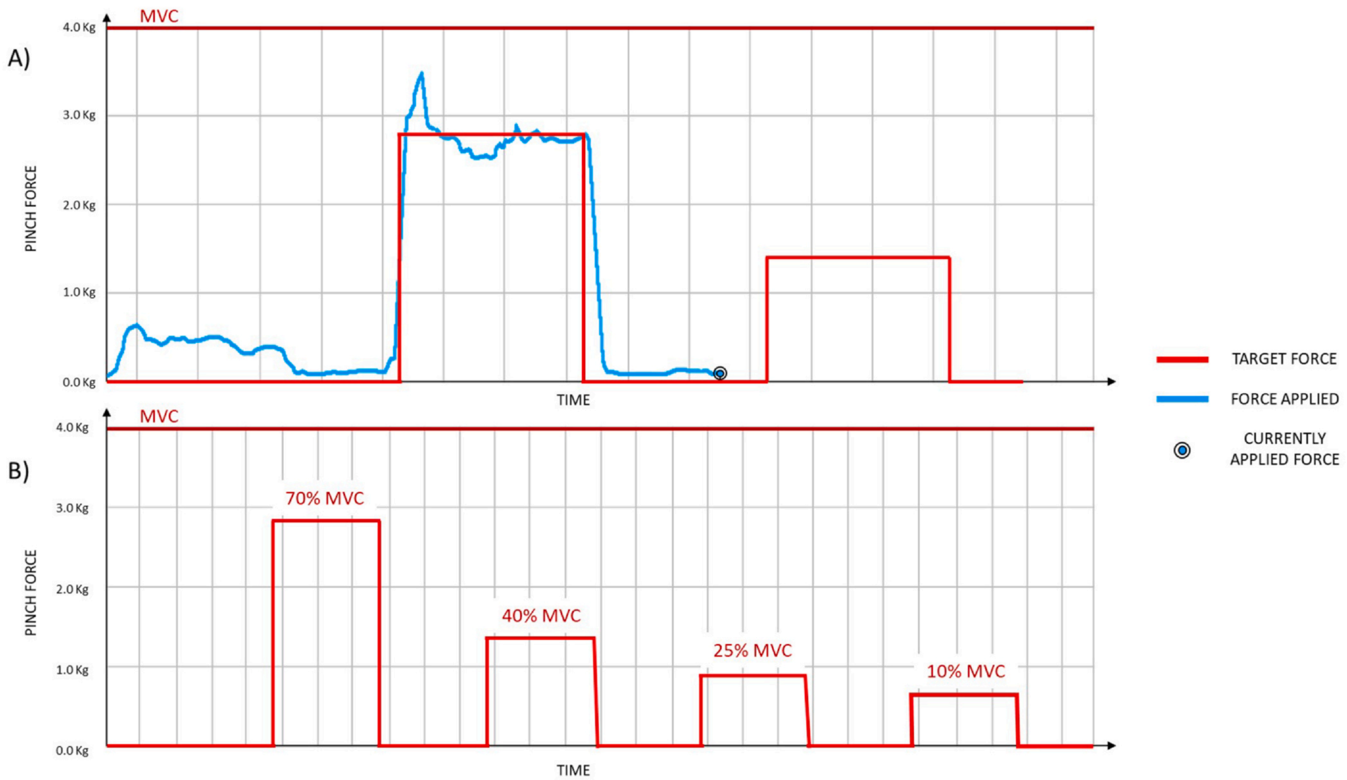

Fig. 4. Graphical representation of the dynamic contraction (DC) test as seeing by the participants.

This approach aimed to maximize the size of the sample, while maintaining a degree of randomness in participant selection. Finally, participants were required to refrain from caffeinated or alcoholic beverages in the six hours prior to starting the session.

Variables

Descriptive variables

Different descriptive variables were evaluated at the baseline through a self-administered questionnaire to understand the sample's characteristics. These variables were assigned sex (at birth) and gender identity, (Male/Female/Other (to specify); M/F/Other), age (years), weight (Kg), height (cm), body mass index (BMI), hand dominance (right/left), and dexterity in both hands. Participants were stratified by sex and assigned to one of the following age groups: 18–29, 30–44, 45–59, 60–74, +75 years. Hand dominance was determined by the Italian version of the Edinburgh handedness inventory.[40] Manual dexterity was assessed through the Rolyan 9 Hole Peg Test (9HPT) in both hands according to Mathiowetz (1985).[41,42]

Outcome measures

The outcome measures are the different variables extracted from SC, DC and BSC. These variables are reported and specified in Table 1 and discussed hereafter.

Time (seconds): The total time acquisition started when the participants' delivered force got into the tolerance range and it stopped when the delivered force went below the lower limit of this range (−10% target force), for more than 1 second.

Mean Distance (MD): The mean value of the modules of the difference between the participants' delivered force and the target force normalized by the target force.[6] This variable represents the accuracy index since it defines the closeness of force to the target, and it is calculated as:

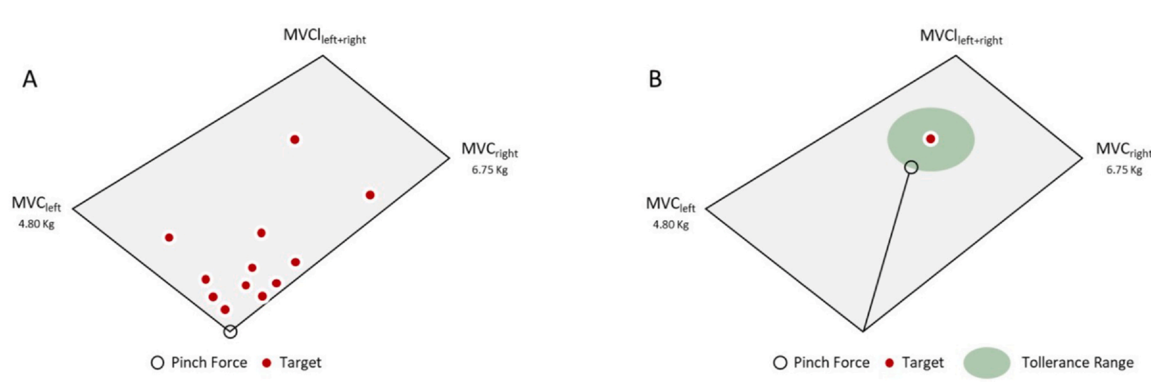

Fig. 5. Graphical representation of the bimanual strength coordination (BSC) test as seeing by the participants.

Table 1
Primary variables of the study

Test	Variables
Sustained Contraction (SC)	• Time (seconds).
Dynamic Contraction (DC)	• Accuracy (Mean Distance, MD); • Precision (Coefficient of Variability, CV).
Bimanual Strength Coordination (BSC)	• Accuracy (MD); • Precision (CV); • Time-to-Reach (TTR).

$$MD = \frac{1}{n}\sum_{i=1}^{n}\frac{|F_{d,i} - F_{t,i}|}{F_{t,i}}$$

where $F_{d,i}$ represents the delivered force at the time sample i; $F_{t,i}$ represents the target force at the time sample i; and n represents the total number of time samples.

Coefficient of Variation (CV): The standard deviation of the participants' delivered force normalized by the mean force.[6,11] This variable represents the precision index since it expresses the variability of force trace and it is independent of the target and it is calculated as:

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n}(F_{d,i} - \bar{F})^2}{n}}}{\bar{F}}$$

where $F_{d,i}$ represents the delivered force at the time sample i; $\bar{F}$ represents the mean force; and n represents the total number of time samples.

In the SC test, time was the only variable collected, while in the DC test, MD and CV were calculated for each epoch ($MD_{1\text{-}4}$, $CV_{1\text{-}4}$). Those measures did not consider the first and the last half-second of each epoch to avoid the effects of the initial force stabilization and any premature cessation of force production. The mean of MD and CV of the four epochs were collected.

In BSC, at first MD and CV were calculated separately for each hand. Taking each hand individually, the task can be represented as 12 epochs of different %MVCs. MD and CV were calculated in all epochs, after removing the first second of acquisition (Right Hand: $rMD_{1\text{-}12}$, $rCV_{1\text{-}12}$, Left Hand: $lMD_{1\text{-}12}$, $lCV_{1\text{-}12}$). Hence, the MD and CV for the BSC test were determined by calculating the mean unilateral values of MD and CV across the 12 epochs, averaged between both the hands.

$$MD_{BSC} = \frac{\left(\frac{\sum rMD_i}{12}\right) + \left(\frac{\sum lMD_i}{12}\right)}{2}$$

$$CV_{BSC} = \frac{\left(\frac{\sum rCV_i}{12}\right) + \left(\frac{\sum lCV_i}{12}\right)}{2}$$

Time-To-Reach (TTR) was calculated as the time needed to enter into the tolerance range as soon as the target appeared on the monitor. The mean of the time to reach the targets was also collected (in milliseconds). We proposed this variable because it differs from MD and CV, since it depends on the time and not on MVC directly.

$$TTR = \frac{\sum TTR_i}{12}$$

Statistical methods

The investigation of the kurtosis and skewness indexes of the probability density functions, and the exploration of the Q-Q plot graphs showed that both primary and secondary outcomes were not normally distributed and were analysed with non-parametric tests.

Descriptive statistics

Descriptive statistics were carried out for each male and female sample and per sex in each age group. Categorical variables (sex, hand dominance) were reported as frequencies, continuous variables (age, height, weight, BMI, pulp pinch maximal voluntary contraction and 9HPT) were reported as mean and standard deviation.

Outcome measures

Normative values of the different variables extracted from SC (time in seconds), DC (MD and CV) and BSC (MD, CV and TTR), since they were not normally distributed, were calculated and here reported as median (Q2), and first quartile (Q1) and third quartile (Q3) as indexes of dispersion. They were calculated and reported divided per sex and age groups of belonging and displayed as boxplots.

Kruskal-Wallis test was conducted in both male and female samples among age groups, to explore differences between the outcome measures and age in both sexes separately.[43] Post hoc tests were conducted using pairwise Mann-Whitney *U*-Tests when the *p*-value of the overall test was <0.05. The statistical significance acceptance level for pairwise comparison has been adjusted for the number of comparisons ($k = 10$) using the Bonferroni Correction.[44] The reported *p*-values in post hoc tests were divided by k. The effect size was reported as eta squared (η^2) for overall comparison between groups and for each reported comparison in all tasks.

Mann-Whitney *U*-test was used to compare the different variables extracted from the three abovementioned tests between males and females, and the variables from SC and DC between the dominant and non-dominant hand. The main effects of the comparisons were reported as eta-squared (η^2).

Results

Descriptive statistics

In total, 328 people were recruited in the study (169 females and 159 males). They were all cisgender, identified their gender to their sex assigned at birth. The sample's characteristics (age, height, weight, BMI, hand dominance, MVC and dexterity for both hands) were summarized in Table 2.

Outcome measures

Sustained contraction

The time variable in the SC test appeared to be stable through the different age subgroups in males in both hands (Tables 3 and 4 and Fig. 6). Instead, in the female sample the descriptive analysis showed a positive gradient which tends to decrease in >75 years (Table 3). Specifically, for between-group analysis, in non-dominant hand between 30–44 years and 60–74 years age groups an effect size of $\eta^2 = 0.143$ was found (Table 4). In the whole population, the time variable reached a $p = 0.27$ between dominant and non-dominant hands. Lastly, a lower duration in SC of males compared to females was found in both dominant ($\eta^2 = 0.032$) and non-dominant ($\eta^2 = 0.015$) hands (Table 5).

Dynamic contraction

Medians of MD, CV of DC test, in both hands, showed a positive trend at the increasing of participants' age (Tables 3,4 and Figs. 7 and 8). In particular, medians of MD and CV of 18–29 years and 30–44 years age groups were lower compared to ones of +75 years subgroups in both hands and sexes (Table 4). A $p = 0.84$ and 0.10 for MD and CV, respectively, were found between dominant and non-dominant hands. Difference between sexes was observed with higher medians of females especially in MD but also in CV in both hands compared to males (Table 5).

Table 2
Descriptive analysis of participants

Age groups	S	N	Mean ± SD					MVC		9HPT	
			Age	RH:LH	Height (m)	Weight (kg)	BMI	DH (kg)	NDH (kg)	DH (s)	NDH (s)
18-29 years	♀	33	24.5 ± 3.1	29:4	1.7 ± 0.1	60.3 ± 12.8	21.6 ± 3.4	3.8 ± 0.8	3.4 ± 0.8	17.3 ± 2.2	18.9 ± 2.1
	♂	35	25.0 ± 2.8	32:3	1.8 ± 0.1	72.4 ± 7.4	23.0 ± 1.9	5.4 ± 1.1	4.7 ± 0.9	18.3 ± 1.8	19.6 ± 1.8
30-44 years	♀	35	36.7 ± 5.0	32:3	1.6 ± 0.1	60.1 ± 10.0	22.2 ± 3.1	3.9 ± 0.9	3.6 ± 0.8	17.4 ± 1.7	18.8 ± 2.0
	♂	32	35.7 ± 4.4	28:4	1.8 ± 0.1	81.7 ± 13.4	25.2 ± 3.6	5.7 ± 1.1	5.5 ± 1.2	18.2 ± 2.3	19.9 ± 3.1
45-59 years	♀	35	53.3 ± 4.3	33:2	1.6 ± 0.1	65.1 ± 13.0	24.2 ± 4.3	3.7± 0.8	3.2 ± 0.8	18.2 ± 2.6	19.9 ± 2.3
	♂	32	52.3 ± 4.2	25:7	1.8 ± 0.1	79.9 ± 11.0	25.3 ± 2.8	5.6 ± 1.4	5.0 ± 1.3	18.8 ± 2.3	20.9 ± 3.0
60-74 years	♀	34	66.0 ± 4.4	31:3	1.6 ± 0.1	69.2 ± 13.7	26.9 ± 5.5	3.3 ± 0.7	2.8 ± 0.6	20.7 ± 4.0	21.8 ± 3.8
	♂	31	65.5 ±4.0	28:3	1.8 ± 0.1	85.4 ± 12.4	27.6 ± 3.2	5.3 ± 1.1	4.8 ± 1.0	22.1 ± 3.5	22.9 ± 2.8
75+ years	♀	32	79.2 ± 3.6	32:0	1.6 ± 0.1	66.9 ± 10.9	25.8 ± 3.5	3.3± 1.2	2.8 ± 0.9	24.6 ± 5.1	26.6 ± 5.6
	♂	29	79.0 ± 4.2	29:0	1.7 ± 0.1	79.4 ± 12.4	26.5 ± 3.2	4.8 ± 1.1	4.3 ± 0.8	25.9 ± 5.3	26.9 ± 4.7
Total	♀	169	51.7 ± 19.8	157:12	1.6 ± 0.1	64.3 ± 12.7	24.1 ± 4.5	3.6 ± 0.9	3.2 ± 0.9	19.6 ± 4.3	21.1 ± 4.5
	♂	159	50.4 ± 19.8	142:17	1.8 ± 0.1	79.6 ± 12.2	25.4 ± 3.3	5.4 ± 1.2	4.9 ± 1.1	20.5 ± 4.3	21.9 ± 4.1

M = mean; SD = standard deviation; S = sex; N = number of people; RH:LH = right hand: left hand; BMI = body mass index; MVC = maximal voluntary contraction; 9HPT = 9 Hole Peg Test; DH = dominant hand; NDH = non-dominant hand; ♀ = female; ♂ = male.

Table 3
Normative values of variables of sustained contraction, dynamic contraction, bimanual strength coordination

Age groups		DH						NDH						BSC					
		SC		DC				SC		DC									
		Time (second)		MD		CV		Time (second)		MD		CV		MD		CV		TTR (ms)	
	Sex	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29 years	♀	94.6	79.7 - 155.1	0.1	0.1 - 0.1	0.1	0.1 - 0.1	114.5	65.7 - 156.3	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.2 - 0.2	0.2	0.1 - 0.2	1164	974 - 1296
	♂	107.3	80.0 - 125.9	0.1	0.1 - 0.1	0.1	0.1 - 0.1	117.8	80.6 - 137.9	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.1	0.1 - 0.2	0.1	0.1 - 0.2	1106	984 - 1261
30-44 years	♀	117.9	81.6 - 148.4	0.1	0.1 - 0.1	0.1	0.1 - 0.1	97.1	68.0 - 133.9	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.1 - 0.2	0.2	0.1 - 0.2	1165	950 - 140
	♂	105.5	78.8 - 119.2	0.1	0.1 - 0.1	0.1	0.1 - 0.1	89.0	60.1 - 128.8	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.1 - 0.2	0.1	0.1 - 0.2	1064	968 - 1217
45-59 years	♀	130.9	98.7 - 159.1	0.1	0.1 - 0.1	0.1	0.1 - 0.1	137.7	85.9 - 171.8	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.2 - 0.3	0.2	0.2 - 0.3	1272	1110 - 1485
	♂	118.4	96.5 - 155.3	0.1	0.1 - 0.1	0.1	0.1 - 0.1	111.1	79.4 - 146.0	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.1	0.1 - 0.2	0.1	0.1 - 0.2	1025	852 - 1211
60-74 years	♀	146.9	110.3 - 200.4	0.1	0.1 - 0.2	0.1	0.1 - 0.1	160.4	96.2 - 181.0	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.3	0.2 - 0.4	0.2	0.2 - 0.3	1416	1264 - 1588
	♂	109.2	77.7 - 134.4	0.1	0.1 - 0.1	0.1	0.1 - 0.1	109.3	72.3 - 158.2	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.2 - 0.2	0.2	0.1 - 0.2	1178	1047 - 1270
75+ years	♀	148.7	99.1 - 180.5	0.1	0.1 - 0.2	0.1	0.1 - 0.2	113.5	72.4 - 193.6	0.1	0.1 - 0.2	0.1	0.1 - 0.1	0.3	0.3 - 0.4	0.3	0.2 - 0.4	1529	1282 - 1820
	♂	115.8	68.7 - 157.5	0.1	0.1 - 0.1	0.1	0.1 - 0.1	107.5	71.5 - 132.7	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.3	0.2 - 0.3	0.3	0.2 - 0.4	1434	1226 - 1711
Total	♀	129.5	88.4 - 170.8	0.1	0.1 - 0.1	0.1	0.1 - 0.1	117.9	79.7 - 172.4	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.2 - 0.3	0.2	0.2 - 0.3	1286	1090 - 1506
	♂	110.8	80.0 - 139.4	0.1	0.1 - 0.1	0.1	0.1 - 0.1	108.1	70.7 - 139.8	0.1	0.1 - 0.1	0.1	0.1 - 0.1	0.2	0.1 - 0.2	0.2	0.1 - 0.2	1155	996 - 1338

DH = dominant hand; NDH = non-dominant hand; M = median; Q1-Q3 = Quartile 1-Quartile 3; SC = sustained contraction; DC = dynamic contraction; BSC = bimanual strength coordination; MD = mean distance; CV = coefficient of variability; TTR = time to reach; ♀ = female; ♂ = male.

Table 4
Between-group analysis with post-hoc tests per sex, divided per age group

Sex	Task	Primary outcome	Hand	X^2	η^2	Mann-Whitney post-hoc tests (η^2) 18-29 years vs 30-44 years	18-29 years vs 45-59 years	18-29 years vs 60-74 years	18-29 years vs +75 years	30-44 years vs 45-59 years	30-44 years vs 60-74 years	30-44 years vs +75 years	45-59 years vs 60-74 years	45-59 years vs +75 years	60-74 years vs +75 years
♀	SC	time	DH	11.7	0.1*	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
			NDH	11.8	0.1*	0.1	0.1	0.1	0.1	0.1	0.1*	0.1	0.1	0.1	0.1
	DC	MD	DH	48.2	0.3†	0.1	0.2‡	0.3†	0.5†	0.1	0.1	0.3†	0.1	0.2†	0.1
			NDH	56.7	0.3†	0.1	0.2†	0.4†	0.5†	0.1	0.3†	0.3†	0.1	0.2‡	0.1
		CV	DH	33.4	0.2†	0.1	0.1	0.1	0.4†	0.0	0.1	0.3†	0.1	0.3†	0.1
			NDH	47.2	0.3†	0.1	0.1	0.2†	0.5†	0.1	0.2‡	0.4†	0.1	0.2†	0.1
	BSC	MD	BIL	73.8	0.4†	0.1	0.1*	0.4†	0.6†	0.1	0.4†	0.6†	0.1*	0.4†	0.1
		CV	BIL	43.3	0.2†	0.1	0.1	0.2‡	0.4†	0.1	0.2‡	0.4†	0.1	0.2†	0.1
		TTR	BIL	32.8	0.2†	0.1	0.1	0.2†	0.3†	0.1	0.2‡	0.2†	0.1	0.1*	0.1
♂	SC	time	DH	5.2	0.1	np	np	np	np	np	np	np	np	np	np
			NDH	4.9	0.1	np	np	np	np	np	np	np	np	np	np
	DC	MD	DH	31.1	0.2†	0.1	0.1	0.2*	0.3†	0.1	0.2‡	0.3†	0.1	0.1*	0.1
			NDH	40.4	0.2†	0.1	0.1‡	0.2‡	0.4†	0.1	0.1	0.3†	0.0	0.1	0.1
		CV	DH	18.4	0.1‡	0.1	0.1	0.1	0.2*	0.1	0.1	0.1*	0.1	0.2‡	0.1
			NDH	29.1	0.2†	0.1	0.1	0.2‡	0.3†	0.1	0.1	0.2‡	0.1	0.1	0.1
	BSC	MD	BIL	55.4	0.3†	0.1	0.1	0.2‡	0.6†	0.0	0.1*	0.5†	0.1	0.5†	0.2†
		CV	BIL	49.2	0.3†	0.1	0.1	0.2*	0.5†	0.1	0.1	0.5†	0.1*	0.4†	0.2‡
		TTR	BIL	32.1	0.2†	0.1	0.1	0.1	0.3†	0.1	0.1	0.3†	0.1	0.4†	0.2‡

X^2 = Chi-square; df = degree of freedom; η^2 = eta squared; ♀ = female; ♂ = male; SC = sustained contraction; DC = dynamic contraction; BSC = bimanual strength coordination; MD = mean distance; CV = coefficient of variability; TTR = time to reach; DH = dominant hand; NDH = non-dominant hand; BIL = bilateral; np = no post-hoc test.
* Significant at 0.05.
† Significant at 0.001.
‡ Significant at 0.01.

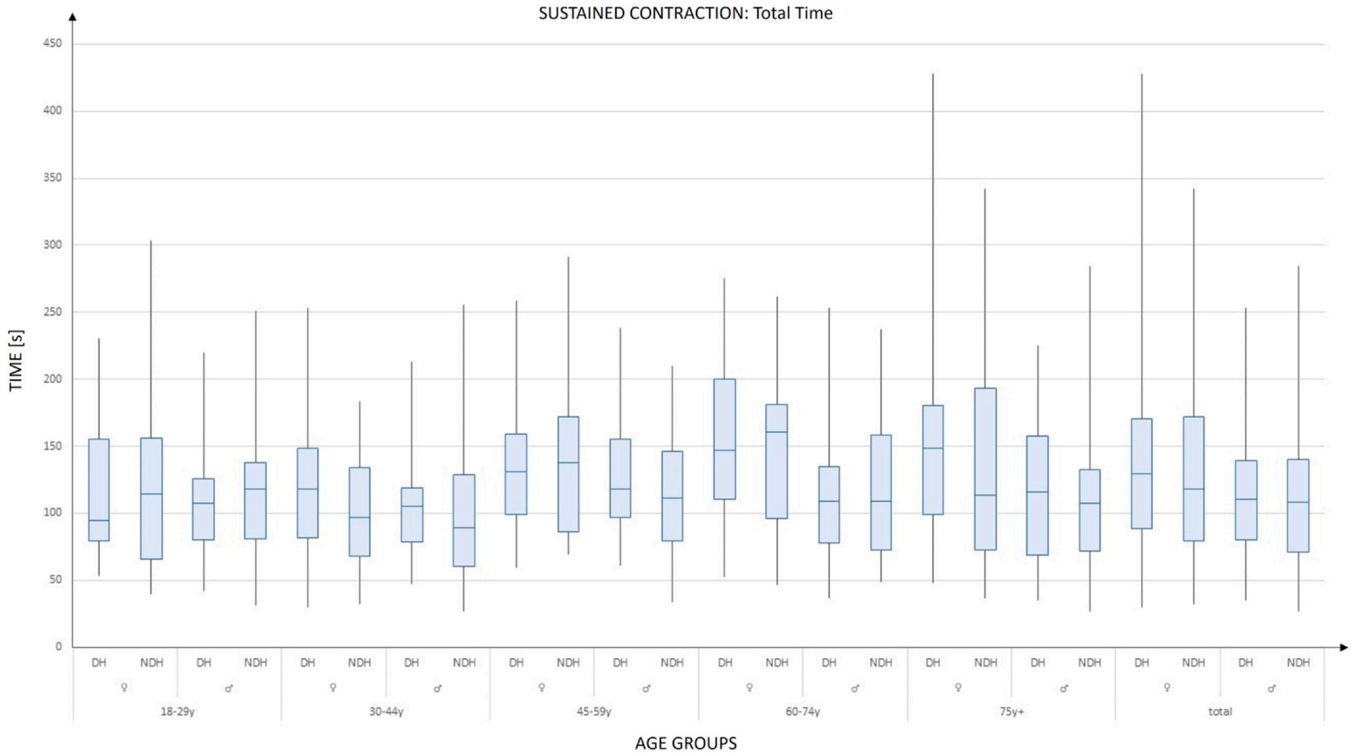

Fig. 6. Box-plots of Time variables in SC divided per age/sex groups. SC = sustained contraction.

Table 5
Mann-Whitney *U* test of comparison between female and male samples

			♀	♂	*U*	η^2
SC	time	DH	129.5	110.8	10666.5	0.1*
		NDH	117.9	108.1	11505.5	0.1†
DC	MD	DH	0.1	0.1	9432.0	0.1‡
		NDH	0.1	0.1	8863.0	0.1‡
	CV	DH	0.1	0.1	10120.5	0.1‡
		NDH	0.1	0.1	9962.0	0.1‡
BSC	MD		0.2	0.2	8524.5	0.1‡
	CV		0.2	0.2	9389.5	0.1‡
	TTR		1286.3	1154.6	9779.0	0.1‡

♀ = female; ♂ = male; η^2 = eta squared; SC = sustained contraction; DC = dynamic contraction; BSC = bimanual strength coordination; MD = mean distance; CV = coefficient of variability; TTR = time to reach; DH = dominant hand; NDH = non-dominant hand.
* Significant at 0.01.
† Significant at 0.05.
‡ Significant at 0.001.

Bimanual strength coordination

Similar findings were found in MD, CV, TTR of the BSC test, which follow the same aforementioned trend with age (Table 3 and Figs. 9–11) of DC. As indicated by the post-hoc tests, +75 years exhibited worse medians in all variables (MD, CV, TTR) compared to 18–29 years, 30–44 years, 45–59 years age groups in both males and females (Table 4). Males showed a tendency of lower values in MD, CV and TTR compared to females (Table 5).

Discussion

The present study investigated normative data of a holistic evaluation of thumb and index force control during PP stratified by age and sex in a population of people without specific diseases.

In general, together with a decline in precision (CV) and accuracy (MD) observed within (DC task) and between (BSC) hands over different age groups, our study identified notable differences between sexes across all evaluated tasks. These findings highlight the importance of understanding age- and sex-related variations in hand function, enabling the proposal of tailored interventions to optimize hand function and enhance quality of life, especially among aging populations and individuals affected by hand-related conditions.

For what concerns the SC tests, no previous studies had investigated endurance in PP contraction in a large healthy sample using different percentages of MVC and no reference values have been documented. There are only studies that investigated handgrip sustained contraction, generally showing no age but sex effect,[45,46] except in one study where a positive age gradient emerged in a female sample.[47] Our results suggested a similar trend in females whose endurance level reached its maximum peak at 60–74 years. This disparity may be attributed to difference in type I and II fibers proportion and in motor units firing rate that differentiate younger from older people.[48,49] Additionally, our findings aligned with those of handgrip endurance tasks, reporting lower fatigability in females compared to males.[45,46] This difference may be partly attributed to the negative correlation between MVC and time,[47] so that sex differences in endurance tests may partially depend on lower maximal strength in females compared to males. Furthermore, there are notable differences in muscle composition, where men typically have a higher proportion of fast-twitch muscle fibers that are more powerful but fatigue faster. Men also generally possess larger muscle mass, necessitating more energy and leading to increased production of fatigue-inducing metabolites. Metabolically, women tend to rely more on fatty acids for energy, which is less fatiguing compared to the glycogen predominantly used by men. Additionally, estrogen, prevalent in women, provides protective effects against muscle fatigue by enhancing mitochondrial function and oxidative capacity, potentially enhancing resistance to fatigue. Lastly, psychological

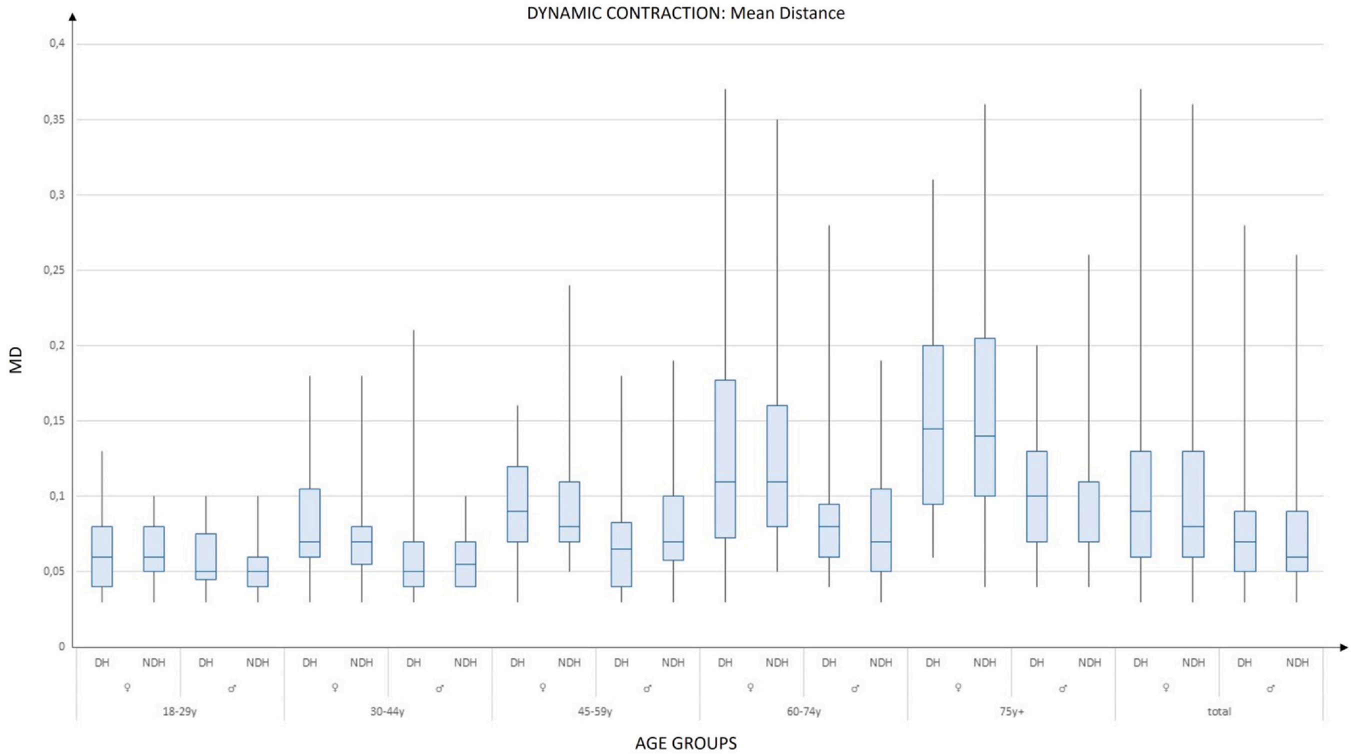

Fig. 7. Box-plots of MD in DC divided per age/sex groups. DC = dynamic contraction; MD = mean distance.

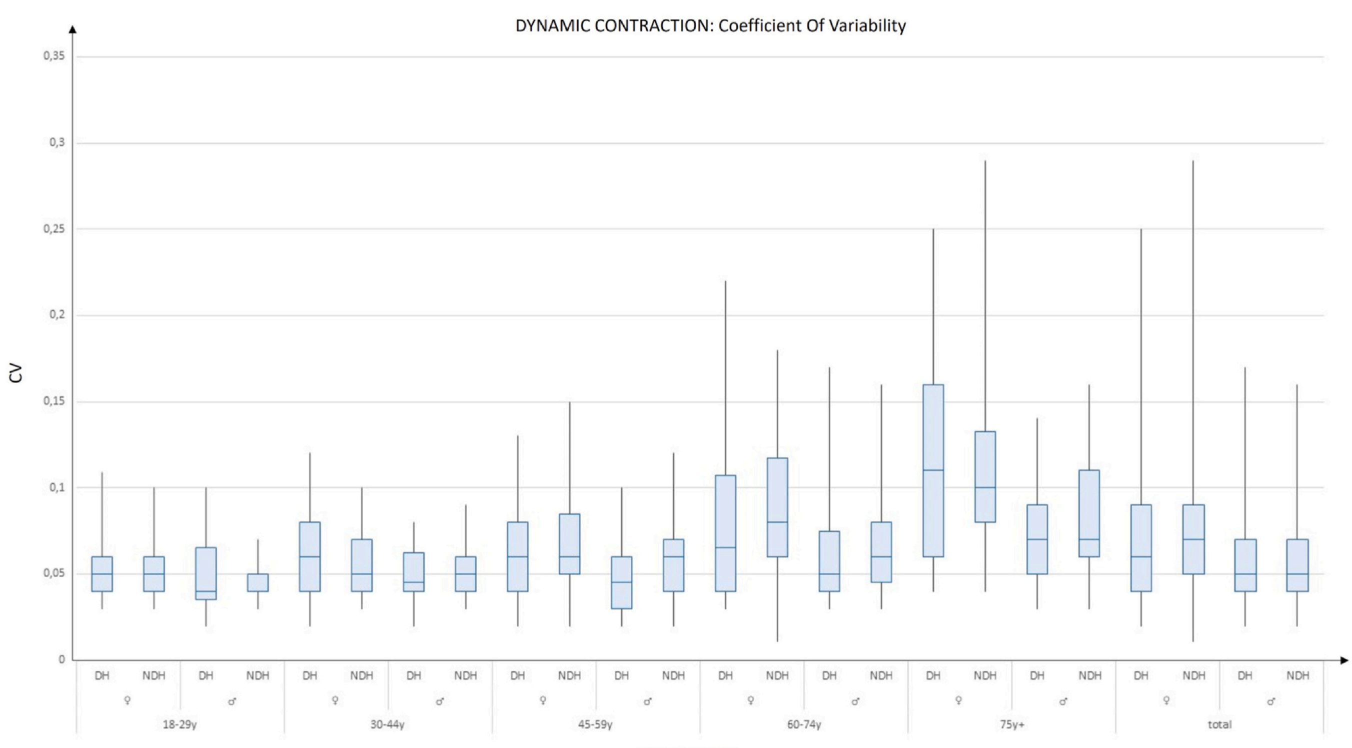

Fig. 8. Box-plots of CV in DC divided per age/sex groups. CV = coefficient of variability; DC = dynamic contraction.

factors such as motivation and pain tolerance can vary between genders, influencing how fatigue is perceived and affecting performance during exercise.[24]

In line with Gordon et al., in which no dominance difference emerged during sustained elbow flexion,[27] pinch endurance does not appear to exhibit lateralization preferences. This may be due to

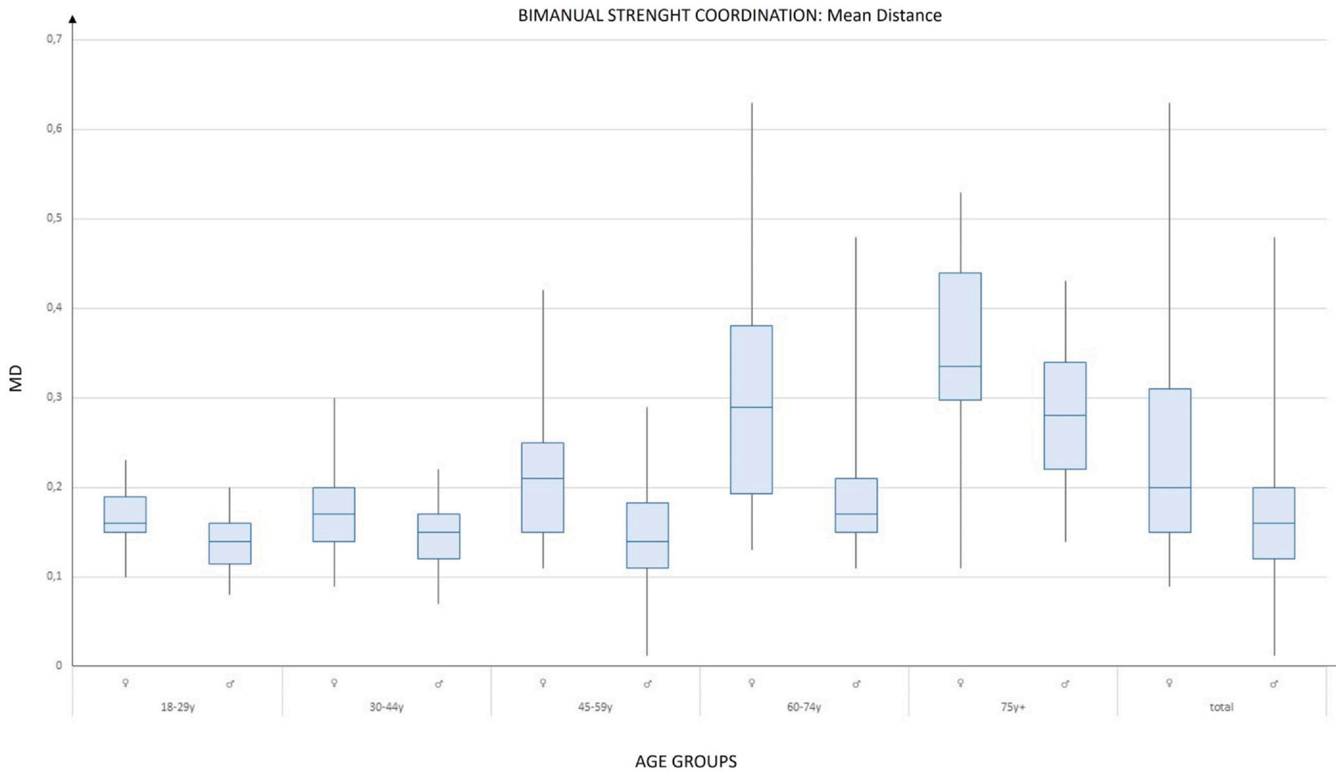

Fig. 9. Box-plots of MD in BSC divided per age/sex groups. BSC = bimanual strength coordination; MD = mean distance.

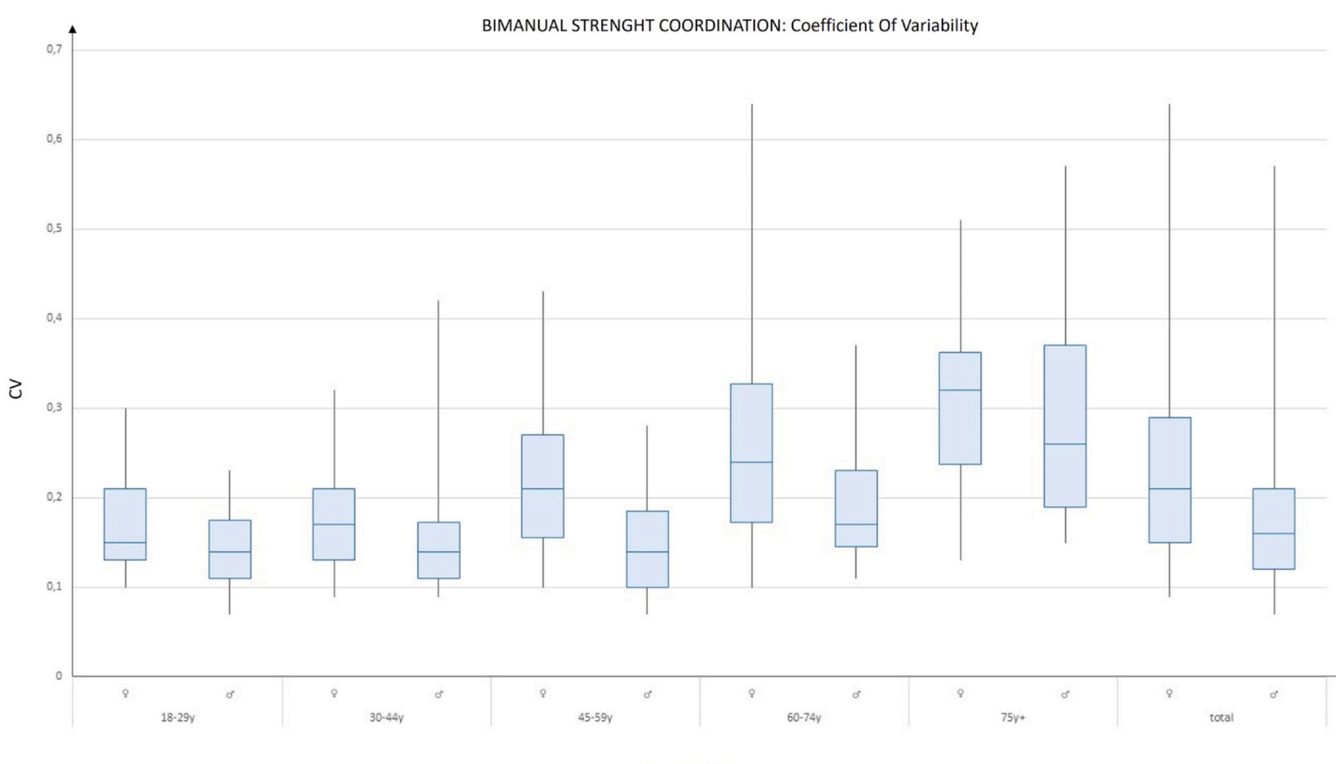

Fig. 10. Box-plots of CV in BSC divided per age/sex groups. BSC = bimanual strength coordination; CV = coefficient of variability.

the fact that endurance activities can be equally distributed between both the dominant and non-dominant hands during activities of daily living.

Our results from the DC test showed that both accuracy and precision, measured by MD and CV respectively, decreased with the increase of people's age in both hands. This finding was in

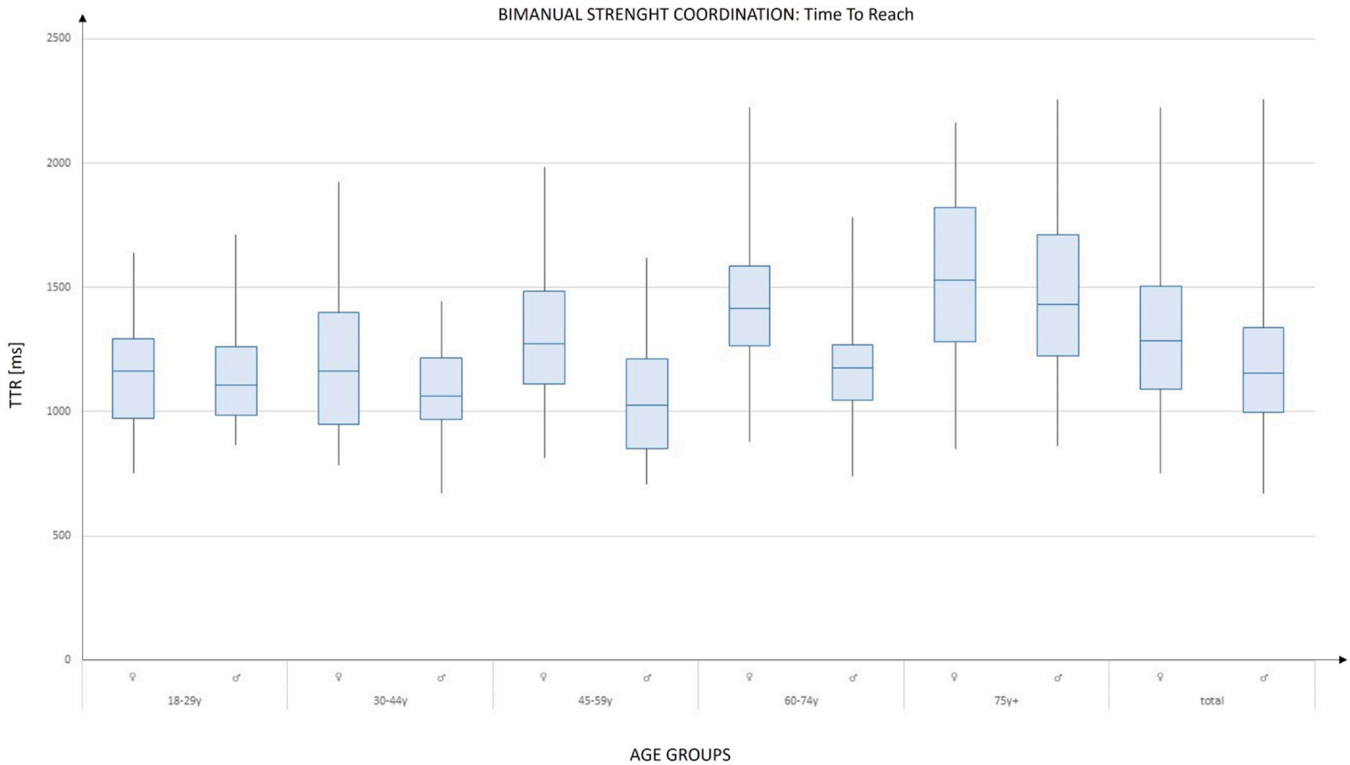

Fig. 11. Box-plots of TTR in BSC divided per age/sex groups. BSC = bimanual strength coordination; TTR = time-to-reach.

accordance to previous results in similar tasks.[11,50] Differences across age groups (Figs. 7 and 8) could be explained by the physiological changes in the neuromusculoskeletal apparatus due to ageing i.e., spinal motoneurons loss, peripheral denervation, increase in motor units size caused by reinnervation of collateral sprouting, reduction in the neuromuscular junction of synaptic vesicles and of post-synaptic receptors.[51] However, it seems that older people, whose hobbies require highly manipulative skills, have performance comparable to younger adults.[52] This evidence may explain the larger scores variability observed in 60–74 years and +75 years subgroups. Hence, it is important to investigate accuracy and precision during a motor control assessment, because these variables can be improved through focussed training, even in older people.[53]

MD and CV were found higher in females than males. The accuracy data retrieved by Herring-Marler et al.[11] seems to oppose to ours since females resulted more accurate than males. This mismatch could be due to the different nature of the studies as their participants performed a task consisting of a low-level force matching whereas DC is based on a variety of higher submaximal force levels. Furthermore, the authors considered a different variable i.e., the Root Mean Square Error (RMSE), and not the MD, to measure accuracy. RMSE is an absolute index that is not influenced by force level. Conversely, MD is a relative index with the target force as denominator. Since the target force is influenced by participants' MVC, while the MVC increases, the MD decreases. Since females showed lower strength than males, we hypothesized that these conflicting results between sexes may depend on the difference between the two aforementioned variables (i.e., RMSE and MD). This hypothesis is also supported by the results of Shim et al.,[26] in which in their ramp force production test RMSE was lower in women, but, after normalization by the MVC, men were more accurate than women both in young and older samples. Regarding the effect of DH and NDH in DC test, our results are in line with De Serres' and Fang's findings,[18] where no difference in precision was observed between the two hands. Hand dominance seems not to influence precision and accuracy of exerted force during a force-matching task guided by visual feedback, in line with previous studies.[28] Visual feedback can indeed play a crucial role in modulating motor commands, allowing individuals to make real-time adjustments and corrections, leading to similar performance levels between the dominant and non-dominant limbs. This feedback helps in maintaining precision and accuracy in force control, regardless of hand dominance.[54]

With BSC test, we investigated the ability to synchronise forces between hands. Not only does this test require organization at the peripheral neuromuscular level, it also involves interhemispheric crosstalk.[55] Results showed that MD, CV and TTR followed a positive trend in participants' age, corroborating the interlimb coordination decline in older adults both in terms of force and dexterity.[23,56,57] Our findings were in line with the anatomic and functional changes in the central nervous system due to ageing. Compared to young adults, older people showed neural over-recruitment in bimanual coordination[58] and a greater loss in white matter that involves the corpus callosum.[59] This important part of the brain is implied in interhemispheric facilitatory and inhibitory interactions, which set the basis for and could affect bimanual coordination.[60,61] Also when it came to sex differences, our results are in line with previous evidence showing males performing better than females in bimanual coordination tasks, guided by visual feedback.[25,62]

In future research, these findings could serve as reference for evaluating alterations in manual force control, both in neuromusculoskeletal conditions and central nervous system disorders. The capacity to sustain a steady force during prolonged contraction hinges on peripheral and central fatigue, and it is influenced by cognitive, neurological, and musculoskeletal factors.[63] In this sense, the SC test on the PP pinch grip holds can be used across to evaluate fine hand function, across a broad of cortical, spinal, neuropathic, and musculoskeletal disorders. This test could be particularly relevant in conditions such as rheumatic diseases,[64] diabetic neuropathy,[65] and multiple sclerosis,[66] where PP grip endurance may reflect disease progression or treatment efficacy.

Using the DC test to evaluate the precision and accuracy of the PP grip could provide a deeper comprehension of fine hand motor control alterations among patients with diverse neuromotor conditions. For instance, Upper Motor Neuron Syndrome presents with reduced fine motor control, inter-finger incoordination, and spasticity,[67] while extrapyramidal diseases like Parkinson's disease, Huntington's disease, and multiple system atrophy are characterized by high force variability, excessive static grip force during manipulations, and a delay in force development.[68–70] In addition, the DC test may serve as a valuable tool in surgical decision-making processes, as it has been observed that different types of surgical interventions for conditions such as thumb osteoarthritis can result in a broad range of variable outcomes among individuals.[71]

Finally, recent studies examining manual coordination in individuals with MS have highlighted deficits in bimanual coordination tasks.[72,73] From this perspective, as a more precise and targeted evaluation, the BSC test on PP could potentially serve as a valuable tool for assessing the efficacy of different medical, rehabilitative, or pharmacological treatments by highlighting more subtle characteristics of the hand motor control in pathological conditions.

Our findings must be interpreted in light of some limitations. We did not manage to include transgender individuals in this study as only cisgender individuals participated. This limitation may affect the generalizability of our findings. Additionally, participants were recruited from a convenience sample specifically from the North of Italy. Although we implemented a randomization strategy across different communities to encompass a diverse range of demographic groups, our analysis did not account for the potential impact of background and sociocultural differences inherent to different geographical areas. Finally, fatigue, both physical and mental, may have occurred, given that the assessment duration lasted approximately an hour, including data collection, explanation, familiarization, and tasks execution. However, to mitigate the impact of fatigue on the variables, multiple breaks were introduced, and the tests order was randomized.

Conclusions

By collecting normative data from a holistic evaluation of hand pulp pinch grip, our study offers a robust reference for future research. Our findings can serve as benchmarks for evaluating hand function across various populations, both healthy and at risk of hand impairments, including those with Multiple Sclerosis, Stroke, Parkinson's disease, Hand Arthritis, among others.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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