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MOTOR CONTROL OF THUMB-INDEX SYSTEM IN HEALTHY POPULATION

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“The hand is the visible part of the brain”

(Immanuel Kant)

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CANDIDATE PROFILE

Alberto Dottor was born in Conegliano (Treviso), Italy, on January 1st, 1990.

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He has been working as a physiotherapist since 2013 specializing in the rehabilitation of people affected by Musculoskeletal Disorders.

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- Hand disorders;
- Motor control;
- Chronic pain.

SCIENTIFIC ACTIVITIES: PH.D. (2017-2020)

Articles

- **Dottor A**, Sansone LG, Battista S, Testa M. Force Control in Unimanual and Bimanual Force-Matching Tasks: a Test-Retest Reliability Study. Article prepared for publication but not submitted;
- **Dottor A**, Sansone LG, Battista S, Testa M. Force Control of Pinch Grip: Normative Data of a Multiparametric Evaluation. Article prepared for publication but not submitted;
- **Dottor A**, Sansone LG, Battista S, Mori L, Testa M. Flexion-extension Strength of the Index-Thumb System in Italian Population. A Cross-Sectional Study to Gather Normative Data. J Hand Ther. Published online 2021. doi:10.1016/j.jht.2021.05.004;
- **Dottor A**, Camerone E, Job M, Barbiani D, Frisaldi E, Testa M. A new visual feedback-based system for the assessment of pinch force, endurance, accuracy and precision. A test-retest reliability study. Hand Therapy. March 2021. doi:10.1177/17589983211002550;
- Job M, **Dottor A**, Viceconti A, Testa M. Ecological Gait as a Fall Indicator in Older Adults: A Systematic Review. Gerontologist. 2020 Jul 15;60(5):e395-e412. doi: 10.1093/geront/gnz113

Conference Proceedings

- **Dottor A**, Camerone E, Job M, Barbiani D, Frisaldi E, Testa M. Test-retest Reliability Of Pinch In Maximum Voluntary Contraction (MVC) And Sustained Contraction (SC) Tasks. Poster presentation at WCPT Congress 2019, Geneva (11/05/2019)
- **Dottor A.** Evaluation of Pinch Force Control in Healthy Population. Oral presentation at PTex-Physical Therapy Excellence 3rd ed, online (13/06/2021)

FOREWORD

This Ph.D. project deals with the most challenging and fascinating topic that I had to face in my first 10 years in the world of rehabilitation as a physiotherapist: the hand.

The hand represents an intricate system of tendons, joints, pulleys, force vectors, proprioceptors, and exteroceptors which work together to satisfy a lot of functions, permits the manipulation of objects, it is the site of the touch par excellence allowing the recognition of objects, and represents a communication means. I could see in my brief experience as a physiotherapist how strongly disabling the impairments affecting hands are experienced by patients. Scars, pain during prehension, tingling at night, deformities, loss of force of hand are a source of extreme discomfort in many people.

“I have a horrible hand” (Woman with traumatic scars on the hand after a motorcycle accident), “My hands are useless” (Young man with bilateral severe Carpal Tunnel Syndrome), “I can't hold the pencil, will I ever go back to work?” (A graphic designer after scaphoid fracture), “I can't knead the pizza dough” (A mother with painful thumb carpometacarpal osteoarthritis).

The stories of patients with hand disorders/diseases are steeped in suffering, despair, and resignation.

Helping these people is highly rewarding as a physiotherapist and represents a real challenge. The main critical points that I encountered in the therapeutic process are on the one hand the lack and difficulty of proposing objective outcomes to evaluate the clinical course and on the other hand the difficulty in the therapeutic proposal.

The hand is complex, permits a wide variability of movements and the rehabilitation programs consist often of stereotyped exercises, intending to restore/increase the strength of specific movements.

Then, usually, exercises are practiced through everyday objects such as clothespins, elastic bands, springs, this is because specific tools are lacking and as a direct consequence sometimes the patient's first impression is trivializing the exercise, leading to distrust and demotivation.

Having clear tools that objectify the improvements and make the exercise more structured and enjoyable would be a valuable help in the clinical setting.

Therefore, I thank Prof. Marco Testa and Prof. Laura Mori for allowing me to deepen the motor control of the hand and to contribute to the advancement in the rehabilitation field.

GENERAL INTRODUCTION

Overview and limits of pinch Maximal Voluntary Contraction (MVC)

The hand is the structure of the upper limb that most relates to the environment, it is a sense organ that provides information on various properties of the object such as weight, size, surface, shape and in response to these, an appropriate movement is produced, which can be of extreme precision or of considerable strength.[1]

It is understandable how impairments involving this body district have important temporary or permanent repercussions in terms of disability,[2–4] making difficult activities of daily life such as opening a bottle, turning a key, using a fork, opening/closing a zipper, leafing a newspaper, writing.[5]

Quantifying the impairments is of primary importance for the clinicians to set the baseline and to define outcomes, and the objective evaluation represents the main phase in which they are collected.

Maximal Voluntary Contraction (MVC) is usually indagated during the objective evaluation of upper extremity to define the level of impairment together with active/passive range of motion of joints, handgrip endurance,[6,7] dexterity,[8] and other more in-depth investigations such as electromyography.[9]

The hand in its repertoire has an enormous variability of grip strategies, MVC is indagated in the most representative ones: the handgrip and the pinch grip.[10]

Handgrip and pinch MVCs are used in both musculoskeletal[11–15] and neurological fields,[16,17] representing indicators to define outcomes, monitor the evolution of hand diseases, and evaluate whether the patient can return to work. [18–20] Their reference values are widely proposed in literature,[21–24] they are considered useful comparators in clinical settings especially in diseases in which both hands are compromised.

The handgrip consists of grasping the object between the fingers and the palm, while the pinch means the grip in which at least two fingers, generally the index and the thumb, are used in association to manipulate an object without contacting the palm.

The two grip types not only involve different muscles of the forearm and hand but also are used for different intentions. The handgrip is involved especially when heavy objects need to be grabbed, it is a power grip, on the contrary, the pinch consists of a precision grip that seldom reaches maximal levels, usually chosen to manipulate small or delicate objects or when force control is required.

Fine manual dexterity consists in an accurate control and inter-digits coordination of fingers' forces, which depend on visual and somatosensory feedback.[25] So that pinch MVC could be restrictive to evaluate the function of the thumb-index system, as confirmed by the low correlation of pinch MVC emerged with hand dexterity and pinch strength control in previous studies.[26,27]

Therefore, the status of thumb-index motor control could be better described by an evaluation that, in addition to maximal strength, analyses other parameters including steadiness, accuracy, endurance, and inter-hand strength coordination.

Normative data of pinch MVC

Normative data is a useful comparator in hand disorders especially in the conditions in which both hands are affected. The reference values describe a defined population at a specific time, and they are widely proposed to relate pinch MVC with age and sex.

In March 2018, a literature search in the Medline database was performed to identify all available studies that established normative data of pinch strength in the healthy population. The query string was ("pinch" AND ("reference” OR "norms" OR "age”) AND ("strength" OR "MVC")).

Manual review of bibliographies of relevant studies and reference lists of relevant literature reviews were used to collect additional records to complement the database’s findings.

All published cross-sectional studies in the English language without time restriction that analysed pinch strength in healthy populations aged over 18 years were collected.

A flow diagram of the selection procedure is presented in Figure 1, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[28]

Nineteen studied matched the inclusion criteria (Table 1).

They showed inconstancy in methods: heterogeneous types of pinch grip were collected (tip, palmar, lateral, and tripod pinches),[29–32] studies used various measurement strategies (mean of three trials or the highest one),[27,33–36] and they analysed hands in different modalities, pinch strength was collected in right/left hand especially in the oldest studies, [37,38] most distinguished between dominant and non-dominant hands.[30,35,39,40]

Although heterogeneity of methods, the results are according to a decline in strength at age increase and a correlation with sex and hand dominance. Whilst a metanalysis cannot be performed to analyse MVC differences between populations, however, there should be differences because pinch strength is influenced by anthropometric factors, culture, and habits.[39] For example Jeune et al.[41] observed a negative gradient from northern to southern European countries in handgrip strength, and, the same difference emerged in key pinch strength between British[38] and Swiss[40] samples. Both studies measured key pinch strength, dividing the sample in age-groups of 5-year intervals, the setting and the procedure were conducted similarly. British sample[38] showed stronger values in all age groups and both sex compared to the Swiss population.[40]

The differences support that normative data are not exportable in other countries, their validity is only in the Population in which they were established. Since no previous reference values of pinch strength were established, there is the necessity to gather them also in the Italian population.

Pinch motor control

The motor control depends on the integration of sensory/visual input, regulation of force output, and intra-, inter-muscles, and inter-limbs coordination. MVC may not be an exhaustive parameter to evaluate motor control, especially in pinch grip: grips that involve pad or tip of thumb and index fingers are not used at maximal level effort but rather they are required in circumstances of fine handling. Fine manipulation requires an in-depth evaluation to guide the therapeutic process, confirmed by the no correlation observed between pinch MVC and dexterity.[26] The recovery of a normal maximum pinch strength may not be necessary nor sufficient. Evaluating other parameters of muscle contraction could better describe hand impairments and act as a bridge for the therapeutic proposal.

Currently, digital measurement systems have been spread in the assessment of pinch MVC. Compared to analogical pinch-meters, the load cell-based measurement systems record all the force traces and display in real-time the exerted force on a PC screen. On one hand, the Visual Feedback (VF) generated could be so used to propose various force matching tasks. On the other hand, the digital signal could be elaborated by the computer, allowing the calculation of many parameters, as the time of contraction or the variability of exerted force. In a literature review, conducted in May 2018 in the Medline database, (query string: ("pinch" OR "hand") AND ("pinch meter" OR "gauge" OR "pinchometer" OR "dynamometer")) AND ("evaluation" OR dexterity OR strength OR "motor control" OR endurance OR "sustained contraction" OR “accuracy” OR “precision” OR “coordination” OR “variability” OR “velocity” OR “handedness”)) various types of tasks based on pinch gauges emerged. Heterogeneous force matching tasks have been proposed, fluctuating force targets,[42–45] constant force targets at low strength level[46] and medium level.[47,48] The main parameters evaluated were the accuracy of exerted force with target force and the force variability,[42,49,50] which were used to investigate the force control with increasing age,[27,51] the effect of VF in the force control in healthy people[52] and patients affected by carpal tunnel syndrome[53]. Ability to grasp, hold and lift objects are essential to the performance of everyday activities. During manipulation, in response to load fluctuations induced by movement, pinch force adjustments occur, in healthy people, through anticipatory neural control mechanisms, those changes are coordinated with the load changes without substantial time lags, producing a stable grip-load ratio.[54]

So that to evaluate the ability to adjust pinch force in response to the inertial load generated by accelerations/decelerations, hold-and-lift tasks were proposed. They require to hold and, maintaining a stable contraction, to lift-on lift-off a measurement system.[55–59]

Another type of task proposed consisted of quantifying digit force vector coordination[60,61]. The possibility to study force vector magnitude, the direction of thumb and index finger separately, and the alignment of opposing digit contact points are interesting because they influence the efficacy of the pinch grip.[62,63]

Based on the aforementioned findings strain gauges are versatile tools that could permit a multiparametric evaluation of pinch motor control. However, despite the enormous potential given by the load cells, only one study[27] was conducted in healthy people to establish reference values but the reliability of the task was not investigated. Therefore, a valid battery of tests, that could better analyses pinch motor control through strain gauges, is not available. In our opinion, in order to have a good impact in clinical practice, evaluation of motor control must consist of easy-to-understand tasks with clear parameters that respond to various domains and that could be measured with ordinary load cells.

Difficulties in clinical applicability occur for example in tasks proposed to quantify digits force vectors coordination because specific force/torque transducers are required to analyze independently the force vector of each finger.[60,61] A similar problem emerges in hold and lift tasks, because the instrumentation requires also a load cell to measure the load force tangential to the surface and an accelerometer to assess force adaptation in relation to the vertical lift.[59] Moreover, the force developed depends also on the weight and the surface type of the instrument, repeatability and normative data may be valid only with the same measurement system and this may be a limit for the assessment in a clinical setting.

So that, the focus of the Ph.D. project revolved around four domains which are possible to investigate through simply load cells: Thumb-Index finger MVC tasks, endurance (sustained contraction), the precision and accuracy of pinch force during a force-matching task (dynamic contraction), and bimanual strength coordination consisting in an in-phase bimanual force-matching task.

Thumb-Index Strength

Besides pinch MVC, also the opposite movement, consisting of combined thumb abduction and index extension (E-MVC), could be a practical estimator of the level of upper extremity impairment.

It has been shown a low thumb abduction strength in many conditions, in first carpometacarpal arthritis,[64] in low median nerve block,[65] in de Quervain's syndrome.[66,67]

Muscles recruited in thumb abduction strength could be beneficial in maintaining the dynamic stability of thumb,[68–70] and consequently need to be indagated to preserve pinch function.

This task could be simply measured with a pinch gauge that permits stabilising the dorsal faces of the thumb and index fingers.[64]

Sustained Contraction

Steadiness and endurance are necessary conditions to every sustained precision grip, as holding a pen and a knife, and to professional activities that involve the thumb.[71] However only Cutts and Bollen[72] proposed a pinch sustained contraction task, to compare fatigue between climber and control, but no reliability study was conducted.

Endurance involves cognitive, neurological, and musculoskeletal factors, ability to maintain a stable force in a prolonged contraction depends on peripheral and central fatigue.[73] As well as endurance tasks in other body districts are largely used in the evaluation of various disorders, both musculoskeletal[7] and neurological one,[74–76] a sustained pinch contraction at medium strength level could be affected in many hand disorders, bringing out deficits in a large pool: cortical, spinal, neuropathic, and musculoskeletal types; and it could be an interesting return to work parameter.

Dynamic Contraction

Grasp and release are central for a healthy hand function. For this reason, hand functional and muscle tone disorders are highly disabling, and they are common findings in upper motor neuron syndrome (UMNS) and in extrapyramidal diseases. In the first condition, there is a reduction in fine motor control, inter-fingers incoordination, and spasticity.[77] The seconds, such as Parkinson’s disease, Huntington's disease, and multiple system atrophy, are characterized by high force variability and excessive static grip force during manipulations and a delay in force development.[43,78–80] Probably, a quick dynamic contraction task could bring out the difficulty in grasp and release that characterise patients with both UMNS and extrapyramidal symptoms.[81–84]

Bimanual Strength Coordination

In many daily activities, objects often are grasped and manipulated bimanually,[85] requiring adequate adjustment not only of within-hand grip forces but also inter-hand ones.

So in bimanual actions, the inter-limb coordination of movements and grip forces is very important to prevent both slippages and squeezing of objects, such as to insert the thread through the needle's eye, break a piece of bread, and pour water into the glass.

Inter-hand movements are assessed by various dexterity tests, such as the Minnesota Rate of Manipulation Test and Purdue Pegboard Manual Test, those tests measures coordination as the ability to grasp, lift and release objects with both hands as quickly as possible.[86–88]

However, with dexterity tests, no information can be directly extracted about interlimb coordination of grip strength, i.e. the control of the force coordination of two hands during bimanual activities.

Bimanual strength coordination represents an increase in complexity of one-handed dynamic contraction, to exert the proper forces of the two hands simultaneously, the interhemispheric transfer is involved.[89]

In the clinical context, the investigation of bimanual force deficits is necessary to define a therapeutic programme to recover bimanual motor coordination that could be affected in older adults,[90] and people with neurological diseases as stroke,[91–93] unilateral cerebral palsy,[94,95] and multiple sclerosis.[96,97]

Before conducting studies on clinical contexts, however, it is fundamental to understand if tasks and their parameters are reproducible and reliable, and able to detect differences among healthy individuals. For this reason, reliability and normative data needed to be investigated.

General organization of the research project

The main goal of this Ph.D. research project was *to develop, investigate the reliability, and gather normative data of a quantitative multiparametric evaluation tool of pinch force control in the Italian healthy Population.* This evaluation was proposed using a digital system based on load cells and visual feedback of exerted force.

Different studies were conducted during the 3 years of Ph.D. training (2017-2020). The results, relative discussions, and implications are reported in the chapters of the present dissertation as follows:

- **Chapter I:** a test-retest reliability study of Palmar Pinch MVC and Sustained Contraction (SC);
- **Chapter II:** a test-retest reliability study of palmar pinch Dynamic Contraction (DC) and Bimanual Strength Coordination (BSC);
- **Chapter III:** a cross-sectional study to obtain normative data of palmar, tip pinch MVC, and E-MVC;
- **Chapter IV:** a cross-sectional study to establish normative data of SC, DC, and BSC.

Summarising, chapters I and II aimed to investigate the goodness of the tasks.[98] While chapters III and IV focused on how the values, resulting from the novel evaluation, were distributed among healthy individuals, analysing the impact on tasks of age, sex, hand dominance and other factors. Furthermore, those studies may represent useful references to compare people with hand disorders.

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Fig 1. Flow diagram of studies through the different phases of the review of pinch strength.

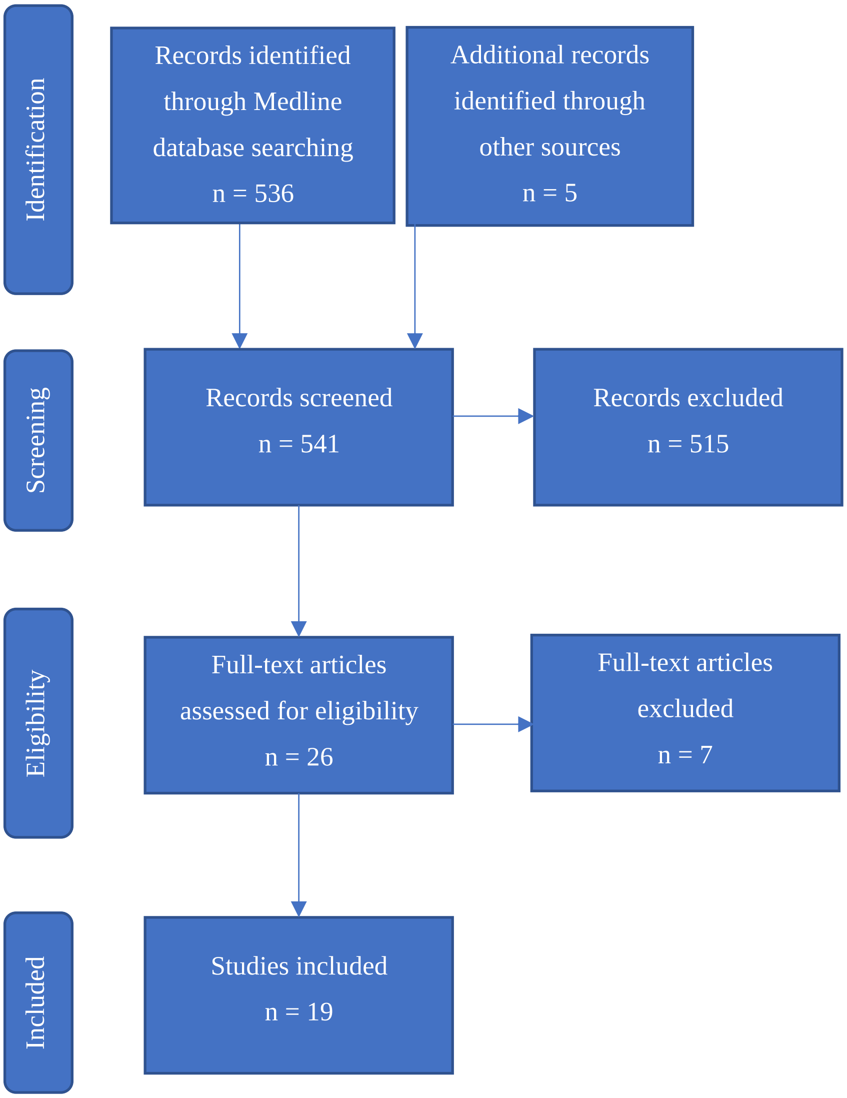

Table 1. Studies included in pinch strength review

Study	Age-groups	Trials	Parameter recorded	Distinction on	Pinch Grip	setting	Sample size
Klum, 2012[99]	18-29y, 30-49y, 50-65y	3	Mean	Side (right/left)	Key	ASHT[100]	750 (363W, 387M)
Nilsen, 2011[24]	Decades from 20y, over 80y	20	Mean and Maximal	Side (right/left)	Tip	same as ASHT	566 (315W, 251M)
Michael, 2015[101]	Decades from 20y, over 50y	3	Mean	Side (right/left)	Key	ASHT[100]	242 (79W, 163M)
Shim, 2013[29]	Decades from 10y to 79y	3	Unspecified	Side (right/left)	Key, Palmar	ASHT[100]	336 (199W, 137M)
Mohammadian, 2014[30]	5y intervals from 20y to 74y, over 75y	2	Maximal	Dominance	Tip, Key, Palmar	ASHT[100]	1008 (482W, 526M)
Young, 1989[102]	10y intervals from 18y to 67y	3 x 12 trials	Mean	Dominance	Key	Same as ASHT	95 (61W, 34M)
Brorson, 1989[103]	5y interval from 21y to 65y	3	Mean	Dominance	Palmar	Same as ASHT	90 (45W, 45M)
Imhran, 1989[104]	5-12y 18-40y 60-89y	2	Maximal	The mean of right and left hand	Palmar for each finger,	Same as ASHT, hand and fingers in a comfortable position	182 (94W, 88M)

					Key, Tripod		
Lam, 2016[33]	5y intervals from 60y to 74y, over 75y	3	Mean	Side (right/left) in right-handed people	Key	ASHT[100]	362 (217W, 145M)
Boatright, 1997[36]	under 60y, over 60y	3	Mean of two closest values	Right in right-handed people	Key	ASHT,[100] wrist in a comfortable position	309 (208W, 101M)
Jansen, 2003[32]	20-39y, 40-59y, over 60y	3	Maximal	Side (right/left)	Key, Tip, Tripod	ASHT, [100] forearm in 3positions: supinated, neutral, pronated	135 (91W, 44M)
Kunelius, 2007[23]	18-25y, 10y intervals from 26y to 65y	3	Mean	Side (right/left)	Key, Palmar	ASHT[100]	161 (23W, 138M)
Gunther, 2008[34]	Decades from 20y to 69y, over 70y	3	Maximal	Side (right/left)	Key pinch	ASHT[100]	769 (403W, 366M)
Werle, 2009[40]	18-19y, 5y interval from 20y to 84y, over 85y	3	Mean	Dominance	Key	ASHT[100]	1023 (507W, 516M)
Puh, 2010[35]	15y intervals from 20 to 79y	3	Mean	Dominance	Tip, Key, Palmar	ASHT[100]	199 (100W, 99M)
Ugurlu, 2012[39]	5y intervals from 15y to 96y	3	Mean	Dominance	Key, Palmar	ASHT[100]	838 (420W, 418M)

Mathiowetz, 1985[37]	5y intervals from 20y to 74y, over 75y	3	Mean	Side (right/left)	Tip, Key, Tripod	Same as ASHT	628 (318W, 310M)
Herring-maler, 2014[27]	Decades from 30y to 79y	3	Maximal	Dominance	Unspecified	Same as ASHT	100 (50W, 50M)
Gilbertson, 1994[38]	5y intervals from 15y to 74y, over 75y	3	Mean	Side (right/left)	Tip, Key, Tripod	ASHT[100]	260 (130W, 130M)

Note: W, Women; M, Men; ASHT, American Society of Hand Therapists

Chapter 1

A new visual feedback-based system for the assessment of pinch force, endurance, accuracy and precision. A test-retest reliability study

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A new visual feedback-based system for the assessment of pinch force, endurance, accuracy and precision. A test-retest reliability study

Abstract

Introduction: Given that pinch is a precision grip involved in sustained submaximal activities, a Sustained Contraction (SC) task could be associated with Maximal Voluntary Contraction (MVC) in hand assessment. To better evaluate the thumb-index system, the test-retest reliability of pinch MVC and SC, measured by a visual feedback-based pinch gauge was assessed.

Methods: 26 healthy participants performed MVC and SC in two separate sessions. SC required to maintain 40%MVC as long as possible and it was evaluated in terms of time, accuracy (Mean Distance between force trace and target force, MD), precision (Coefficient of Variability of force trace, CV). MD and CV analyses were conducted dividing the SC task into three equivalent time stages (beginning, middle, exhaustion). Relative Reliability (RR) was measured by Intraclass Correlation Coefficient, and Absolute Reliability (AR) was measured by Standard Error of Measurement and by Bland-Altman plot.

Results: MVC and Time showed high RR and AR in both hands. RR of MD and CV in right hand was excellent in the beginning and middle stages, and fair in the exhaustion one, showing decreasing reliability as fatigue increases. In the left hand RR of MD and CV was generally lower. MD showed excellent reliability in the beginning stage and good reliability in the other stages. CV showed fair relative reliability at both beginning and middle stages, excellent in the last one. Conversely, it was observed high AR of MD and CV in all stages in both hands.

Conclusions: All indices are reliable to assess motor control of thumb-index pinch in both hands.

Background

Since the 1970s, the measurement of pinch maximal voluntary contraction (MVC) is commonly used in clinical practice as an objective evaluation of hand force. It allows to test treatment effectiveness, monitor the progress of recovery, and evaluate whether the patient is able to go back to work.[1–6] Force is generally measured with mechanical or hydraulic pinch-meters. The former is based on a spring of known resistance and a pointer on a dial shows the compression level of the spring. The latter measures force by registering fluid pressure variation.[7] Throughout the last decade, a new-generation of digital pinch-meters have been shown to be as reliable as the analogue pinch gauges to assess pinch MVC.[8,9]

However, pinch is a precision grip,[10] which is used at submaximal force levels even in prolonged activities, especially if they involve handling small objects as in handwriting, cutting with a knife, using tweezers and hand stitching. The motor control cannot be represented only by MVC, its evaluation should be more oriented towards the pinch function.

The more sophisticated strain gauges are equipped with a graphic user interface that provides real-time visual feedback (VF) of the exerted force. Consequently, these measurement systems have been used to propose various force-matching tasks, allowing an evaluation of the function of pinch that encompasses not only maximal strength but also other features, such as the force variability.[11–13] Moreover, VF has been shown to successfully replace the sensitive afference in those cases where the somatosensory system is impaired, such as carpal tunnel syndrome.[14] This demonstrates that VF can be a useful aid in rehabilitation programs.

Visual cues allow a better force modulation so that exerted force matches the force target, whilst without visual cues people tend to increase their "safety margin" imparting greater strength[15] and over time force declines faster.[16] Besides, when stressors or lack of sensory feedback occur, VF modulates the descending motor command, limiting force fluctuation.[17,18] If these devices were shown to be reliable, their implementation would allow on the one hand, to better and objectively measure the force control and, on the other, to propose specific exercises.

Here, we describe and evaluate the reliability of the pinch sustained contraction (SC) task, measured by a digital pinch meter. This task has not been previously studied. The SC task assesses the ability to maintain a stable pinch force until exhaustion in terms of duration and force control. Endurance tasks are widely used in the clinical setting, for instance, reduced resistance is an indicator of both musculoskeletal and neurological disorders.[19–22] Accordingly, SC could be of interest to analyze fatigue of central or peripheral origin in the impaired hand. Moreover, SC provides information of force control through accuracy and variability of exerted force, allowing the hand therapist to obtain further information for therapy. Although the validity of an instrument is assured by its manufacturer's routine quality controls, consistency of a measure needs to be investigated before the newly developed devices are implemented in clinical or in experimental contexts. Accordingly, the present study aims to investigate the test-retest reliability of pinch MVC and SC, measured by a visual feedback-based pinch gauge.

Materials And Methods

Study design

A test-retest reliability study of MVC and SC tasks of index-thumb palmar pinch in a healthy population was developed according to Guidelines for Reporting Reliability and Agreement Studies (GRRAS).[23]

Participants

A convenience sample of 26 healthy young adults (13 men, 13 women) was recruited in this study. Participants were students and young researchers recruited from the University of Genoa. Ethical approval was obtained from the Ethics Committee for University Research of the University of Genoa (protocol CERA2020.06). All participants provided written informed consent before entering the study.

The exclusion criteria were a history of acute, sub-acute or chronic pain, injuries or neuromusculoskeletal diseases in the upper limbs, and visual impairments (the use of corrective lenses was allowed).

Participants were prohibited from consuming caffeine 12 hours before each experimental session as well as alcohol, any drugs and refrain from new physical activities during the assessment period.

Adherence to guidelines was verbally checked upon participant arrival. Data on age, height, weight and handedness (identified as the hand that participants used for writing) were collected.

System of measurement

The system consisted of (Figure 1):

1. two customized load cells, namely two force sensors (P502.F-S/250N, Deltatech, Forlì-Cesena, Italy), with a measuring range of ±250N and a nominal sensitivity of 2.880 ±0.150 mV/V;
2. the strain gauge amplifier, a Wheatstone Bridge circuit that determines the relative changes in electric resistance of the two sensors, and the analog-to-digital converter that digitalizes the input signal and makes it available to the PC, connected via USB;
3. the software to analyze data and provide friendly-user interface to rater and participant.

Experimental design

Since multiple test measurements would have required significant effort from participants resulting in a potential dropout, repeatability was assessed in two experimental sessions. The procedure was conducted by a single rater, who had been previously trained in the use of the measurement system and had practised throughout a pilot study. Test-retest reliability was tested in two sessions, spaced out by 4 to 6 days to avoid memory and learning effects. The two sessions were designed to be as similar as possible: evaluation was kept constant for every participant, with a resting time of 1 minute between each task. Since motivation and concentration could influence the outcomes of a sustained task,[24] the participant assessor interaction was standardized by a defined script, describing how to guide and to motivate participants during the test. At the end of each session participants did not receive any comments related to their performance.

Position was standardized according to the American Society of Hand Therapists.[25,26] Participants were seated on an adjustable chair, whose height was set in order to position their arms in natural abduction and rotation, with the elbows leaning on the table and flexed at 90 degrees, wrists dorsiflexed at 30 degrees, and 15 degrees of ulnar deviation. Chair height was kept constant between test and retest sessions and trials. The device was gripped using the first and second fingers, in two points palmar pinch position, with thumb and index parallel and the remaining fingers clenched. Participants sat at 85 cm from the computer screen.

The experimental protocol was made up of two tasks, for both test and retest sessions:

1. *Maximal Voluntary Contraction (*MVC*)*, participants were asked to perform their maximum pinch force in two repetitions within 10 seconds, and the highest score was recorded (Figure 2);
2. Sustained Contraction (SC), participants had to match a force target set at 40% of their MVC (40%MCV) (Figure 3). The force target was represented by a horizontal line displayed on the monitor. The task required a) precision and accuracy, by keeping the cursor on the line, and b) endurance, by maintaining the contraction until exhaustion. The participants did not have any time reference to estimate duration. In order to avoid excessive fluctuations, a variability range was displayed around the force target (±10%MVC), and the task was automatically interrupted if the cursor exited from such range for longer than 1 second.

The two tasks were performed with both hands and the hand order was randomized by Excel random function.

Prior to start of the protocol each participant was instructed on the procedure and familiarized with the measurement system.

Data acquisition and analysis

Participants’ data were registered by the acquisition software and subsequently analyzed in MATLAB®.

SC test was assessed in terms of performance duration (time), accuracy and precision. Time was calculated by removing the first 10 seconds and the last 2 seconds of the SC registration, in order to control possible initial force stabilization, as well as possible strength drops at the end of the SC test, which could affect both accuracy and precision scores.

In order to better characterize how fatigue impacts on the accuracy and precision variables in function of time, the test was divided into three equal episodes of time describing the beginning (beg), the middle (mid), and the exhaustion (end) stages of the SC test. It was expected that fatigue impact would be minimal in the initial stage, progressively increasing in the middle and reaching the peak in the last one. Accuracy and precision were calculated for each stage.

Accuracy of SC performance was assessed using the Mean Distance (MD):[27,28] the mean value of the modules of the difference between the participants’ force data samples (F_i) and the force target (40%MVC) across the time duration, normalized by the target force.

Precision was assessed using the Coefficient of Variability (CV):[13] the standard deviation (SD) of the force signal normalized by the mean force ($\bar{F}$).

The two variables were calculated as follows:

$$MD = \frac{\sum |F_i - 40\%MVC|}{n_i * 40\%MVC} * 100 \qquad (1)$$

$$CV = \frac{\sqrt{\frac{\sum(F_i-\bar{F})^2}{n_i}}}{\bar{F}} * 100 \qquad (2)$$

Statistical analysis was performed using SPSS 24.0.0.0 (SPSS Inc., Chicago, IL, USA). Normality was checked by investigation of the kurtosis and skewness indexes and exploration of the Q-Q plot graphs of dataset. Relative reliability was assessed by Intraclass Correlation Coefficient (ICC) estimates and their 95% confidence intervals based on single measurements, absolute-agreement, and 2-way mixed-effects model. ICC estimates have been interpreted according to guidelines previously suggested in literature: values less than 0.39 indicate poor reliability; values between 0.40 and 0.59 suggest fair reliability; values between 0.60 and 0.74 indicate good reliability; values greater than 0.75 indicate excellent reliability.[29,30] To assess absolute reliability, differences between measurements of trial 1 (recorded during the test session) and trial 2 (recorded during the retest session) were plotted against the average of the two measurements, as described by Bland-Altman's 95% limits of agreement (95%LoA).[31] By looking at whether the mean error is close to zero, it is possible to establish how consistent the measurements have been. The mean error (kilograms) plus-or-minus 1.96 standard deviations describes the interval in which the measurement error falls 95% of the time. Absolute reliability was also assessed by calculating the Standard Error of Measurement (SEM), which provides an absolute indication of the error variability around the mean. SEM was also expressed in terms of percentage (SEM%) for both MVC and Time.[32] The less the error variability, the more reliable the measurement is. SEM was calculated with the following formula: SDtest $*\sqrt{1-ICC}$.

Results

Twenty-six right-handed healthy participants (mean ± standard deviation: age, 27.3 ± 4.4yrs; height, 168.0 ± 6.3 cm; weight, 64.4 ± 9.3 kg) were enrolled between June and July 2020. All the variables followed a normal distribution. Table 1 reports mean and standard deviation of MVCs and SCs parameters.

Maximal voluntary contraction

As shown in Table 1, the between days relative reliability was excellent, ICC >.750 in both hands. Absolute reliability was also good, as described by SEM, SEM% (7.62% and 6.3%, right and left sides respectively) and by Bland-Altman plots (Figure 4).

Sustained contraction

Time

Healthy participants resisted, on average, 150 s in the SC. As shown in Table 1, ICC was higher than 0.75 in both hands, showing excellent test-retest reliability for Time. Absolute reliability was also good as indicated by SEM, SEM% (17.9% for Right Hand and 16.5% for Left Hand) and as graphically checked by Bland-Altman plots (Figure 5).

Mean distance and coefficient of variability

Relative and absolute reliability measured with ICC and SEM, for both MD and CV, are shown in Table 1.

Measures of both MD and CV for right hand showed excellent relative repeatability during the beginning and middle stages, and fair (MD) or poor (CV) reliability during the exhaustion stage. Differently, MD for the left hand displayed excellent relative reliability in the beginning and good in both middle and exhaustion stages, when fatigue increased.

CV for the left side showed fair relative reliability in the beginning and in the middle stages, and excellent reliability in the exhaustion one.

Absolute reliability was good as assessed by SEM (Table 1) and graphically represented by Bland-Altman plots (Figure 6).

Discussion

The present study investigated the relative and the absolute reliability of pinch MVC and SC assessed by a visual feedback-based system.

Maximal voluntary contraction

MVC relative reliability reported by the system of measurement for both the right and the left hand was excellent, in line with previous repeatability studies in healthy populations.[9,33] To achieve a complete awareness, MVC reliability should also be investigated in absolute terms, thus providing information about the magnitude of variability between tests. Indeed, MVC is often used clinically to monitor the evolution of a disease or a rehabilitation programme; therefore, it is important to know if MVC changes over time are dependent on clinical developments rather than measurement errors. In this respect, our findings, expressed by mean of Bland-Altman plots (Figure 4), SEM and SEM%, showed high consistency between test-retest values and good absolute reliability for both hands.

From our experience, in the assessment of maximal pinch strength, upper limb position kept during the test is an important aspect to consider carefully.

Specifically, the arm, hand and finger positions must be strictly standardized in order to obtain a reliable MVC. Several studies have thus highlighted that changes in the arm position affect the strength performance: the strength decreases especially over 90 degrees of elbow flexion, in the pronated forearm and in maximum flexion and extension of wrist.[2,34,35]

Sustained contraction

Time

Even though the Time parameter was within the excellent reliability range, it had lower reliability than MVC. Interestingly, Bland-Altman plots showed that the time dataset presented a heteroscedastic distribution. Indeed, the test-retest variability increased accordingly with the duration of the SC test. Precisely, the mean difference between test and retest was doubled in participants that lasted longer than 150 s (mean difference on average 38,5 s) compared to those in whom it lasted less than 150 s (mean difference on average 22,5 s). This suggests that the longer the performance, the less accurate will be the reproduction of the same performance in the next session. Furthermore, the lower level of reliability in SC compared to MVC test can be explained by the fact that SC performance is more influenced by cognitive factors – e.g. concentration, motivation, mental exhaustion, focus of attention - than MVC performance.[36] Overall, time can be deemed reliable and, since pinch grip is involved in many submaximal sustained contraction tasks, it may represent a useful additional outcome in the assessment of hand functional changes induced by rehabilitation or by pathology progression. Unfortunately, these findings cannot be compared with other studies because the present work is the first, to our knowledge, to assess pinch endurance adopting time as outcome measure. Only

Cutts and Bollen[37] investigated a similar endurance task, by comparing climbers and controls in a 50%MVC pinch task until exhaustion.

However, the authors assessed the performance by looking at the “total work” defined by the integrals of the force-time curve (kiloNewtons*seconds), whereas its reliability was not investigated. Moreover, total work is a derived quantity depending on force and on time, that does not permit a straight understanding of the capacity of a participant’s endurance. It seems that time is more suitable to compare the same participant’s follow-up, as shown by several studies conducted in other body regions.[19,24,38,39]

Mean distance and coefficient of variability

ICC was not excellent in all stages for MD and CV (Table 1). In this regard, it’s worth mentioning that the ICC statistical test is highly influenced by the variability of the sample, where low variability between participants and homogeneous dataset lead to low ICCs.[40–42] The nature of the SC assessment artificially constricted the data to be homogeneous because a) the goal of the test was to keep the cursor precisely on the force target line, and b) the cursor had to lay within the variability range of ±10%MVC, and potentially leading to low relative reliability. For this reason, absolute reliability becomes relevant, providing a better understanding of the reliability of the SC test. Absolute reliability assessed with Bland-Altman limits of agreement and SEM suggested good reproducibility of MD and CV for both hands in all stages of fatigue (Figure 6). Indeed, mean differences were always close to zero and limits of agreement small enough to consider the measures consistent between trials. Specifically, in MD the largest interval of agreement between test and retest was found in the exhaustion stage, when the task was performed with the left hand (95%LoA: from -7.0 to 5.0), this range still remains tight, in accordance with a small SEM. Similarly, Bland-Altman 95% limits of agreement suggested reproducibility of CV for both hands in most of the fatigue stages (Figure 6). All mean differences were extremely close to zero, and limits of agreement were always small enough to suggest consistency of measurements over time. The largest disagreement in CV was found in the final fatigue phase, when the task was performed with the right hand (95%LoA: from -5.8 to 6.0). This range is still tight, in line with a small SEM.

Collectively, MD and CV limits of agreement and error variability were extremely small. Some degrees of freedom are embedded in the nature of those tasks which require human motor control, due to different postural compensatory mechanisms, motor strategies or fluctuation of attention. Specifically, motor strategies to counterbalance the raising of fatigue have been observed. For example, some participants tended to control force expression underneath the target, keeping the cursor on the lower border of the tolerance range. Other participants tended to create a sinusoidal pattern, swinging up and down from the target line. Nevertheless, test-retest variability for MD and CV only fluctuated by a few percentage units both between participants and between trials, suggesting accuracy and precision of the SC trial in assessing pinch force during all stages.

Interestingly, we also observed that test-retest reliability of MD and CV decreased from one stage to another, in both relative and absolute terms. This is not surprising because, over the SC trial, fatigue progressively increases together with a lessening of motor control, thus making the performance clumsier and inconsistent. The only exception was the CV in the left hand, in which the exhaustion stage showed the best relative reliability. However, since that specific stage also showed the highest SEM, those results could be due to the high variance between participants. During the beginning and middle stages both MD and CV showed lower relative reliability in the left hand than the right. Lower reliability in the left hand could be explained by the fact that all the participants were right-handed, with less control over the non-dominant hand.[43]

Overall, since force steadiness is specific for each participant, especially in the beginning stage (good-to-excellent ICCs), MD and CV could be interesting parameters to describe clinical improvements in pinch motor control. They provide information about the ability to keep strength as close as possible to a specific target (accuracy) and about the variability of delivered strength (precision). Moreover, progress could be monitored in the absence of fatigue, when fatigue increases, and when fatigue is at its peak.

Lastly, the pinch steadiness correlates with different dexterity tasks, more strongly so than MVC, emphasizing the importance of a multiparametric assessment.[44]

Many hand activities requiring sustained contractions of thumb and index, both in isolation or simultaneously (i.e. handwriting and force steadiness) could be affected by both neuromusculoskeletal and central nervous system disorders, as was shown in body parts other than hand.[20,45–50]

For this reason, SC could be a precious, time-efficient test to be implemented for the assessment of the hand, providing reliable quantitative parameters of duration (time), accuracy (MD) and precision (CV).

Cognitive, neurological and musculoskeletal domains are also involved in endurance and steadiness abilities, therefore controlling intersession fluctuations of SC is more complex compared to the MVC task. It follows that the setting, the position during the test, substances intake, level of encouragement and motivation, and lastly level of fatigue prior to starting the test should be firmly considered by the clinicians, especially during the evaluation of sustained contraction tasks.

There are limitations to consider in the current study. The participants were not randomly selected and were representative of a restricted portion of population, therefore results can only be generalized to young healthy right-handed adults.

Future research should investigate reliability across other ages, for instance in children and elderly and across, left-handed and different clinical populations and it should establish reference values across ages and sexes.

Conclusion

The visual feedback-based system assessed in the present work represents a reliable tool to measure MVC and SC. In particular, the SC task and its related parameters may contribute to assess pinch motor control in terms of endurance, accuracy and precision especially in disorders in which fatigue represents a main symptom or that are characterized by a lack of coordination in muscles output, and in all those conditions that require ability to maintain a stable submaximal contraction over time. Pinch gauges matched with visual feedback could be effectively integrated in the rehabilitation plan as support for specific force, endurance or motor control exercises.

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Fig 1. System of measurement (load cells and signal amplifier) and hand position during tasks.

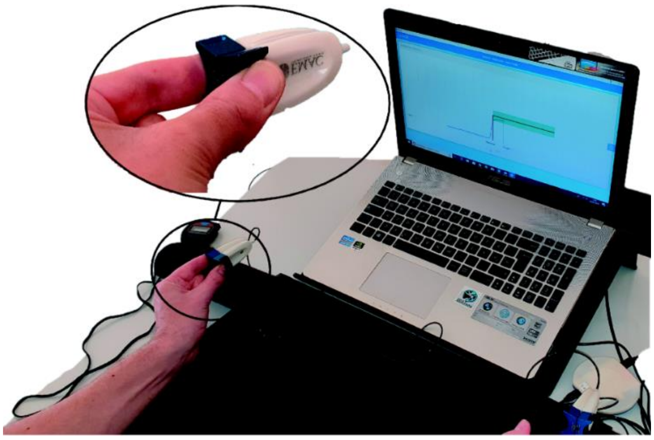

Fig 2. Graphical user interface displayed during maximal voluntary contraction task.


Selected patient : prova a

MVC evaluation

4 remaining seconds

Fig 3. Graphical user interface displayed during sustained contraction task.

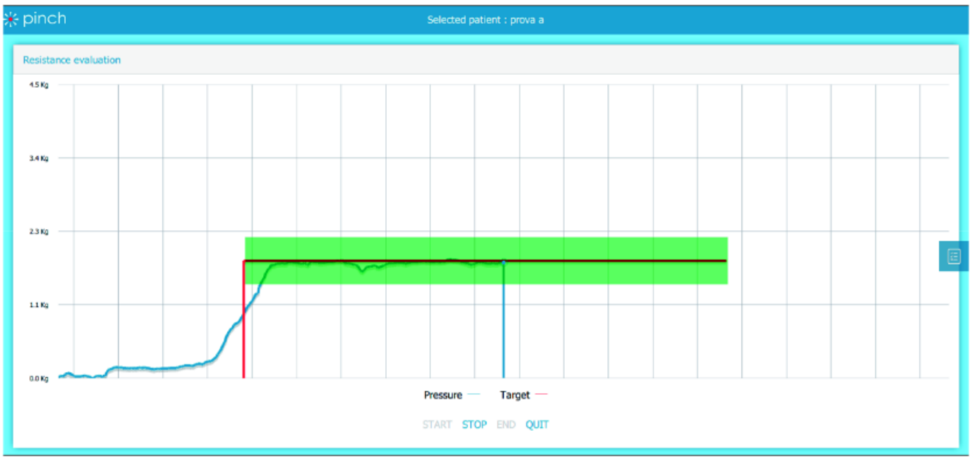

Fig 4. Bland-Altman plots of MVC in right and left hands, the central line represents the mean difference between test and retest values; the upper and lower lines characterize the upper and lower 95%LoA. MVC: maximal voluntary contraction; 95%LoA: 95% limits of agreement.

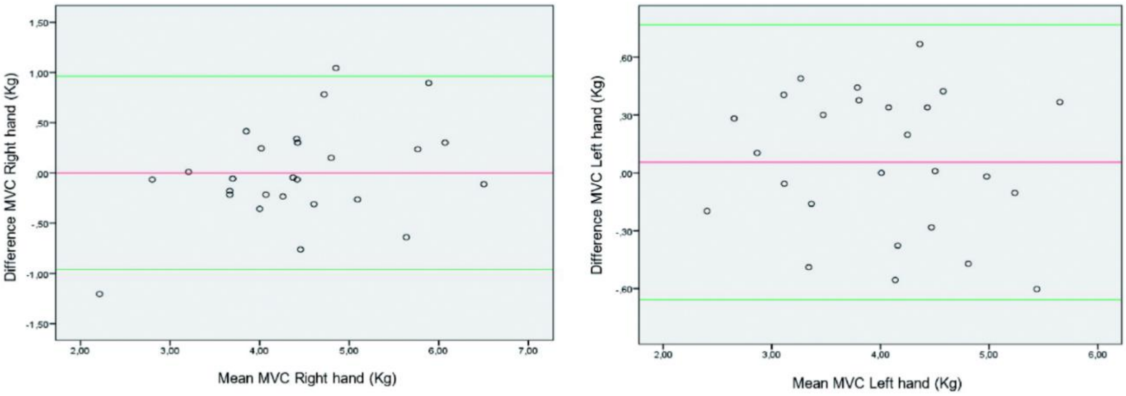

Fig 5. Bland-Altman plots of *Time* in right and left hands, the central line represents the mean difference between test and retest values; the upper and lower lines characterize the upper and lower 95% limits of agreement.

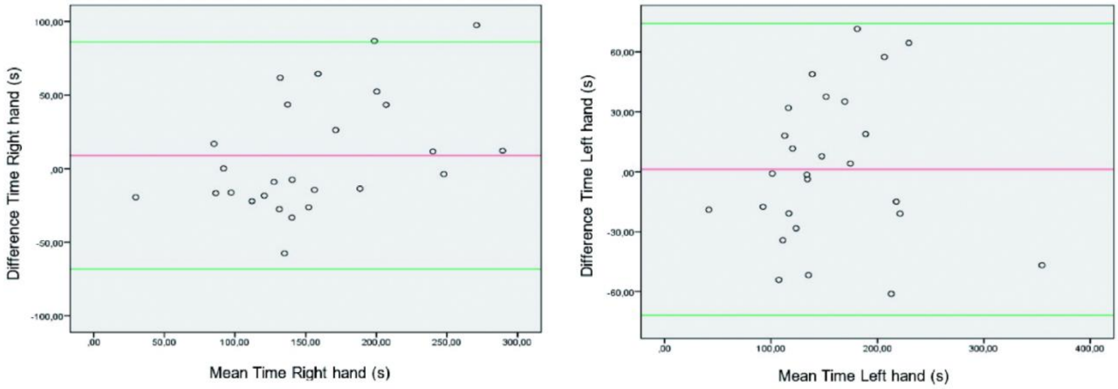

Fig 6. Bland-Altman plots of MD and CV in beginning, middle and exhaustion stages in both right and left hands, the central line represents the mean difference between test and retest values; the upper and lower lines characterize the upper and lower 95%LoA. MD: mean distance; CV: coefficient of variability; 95%LoA: 95% limits of agreement.

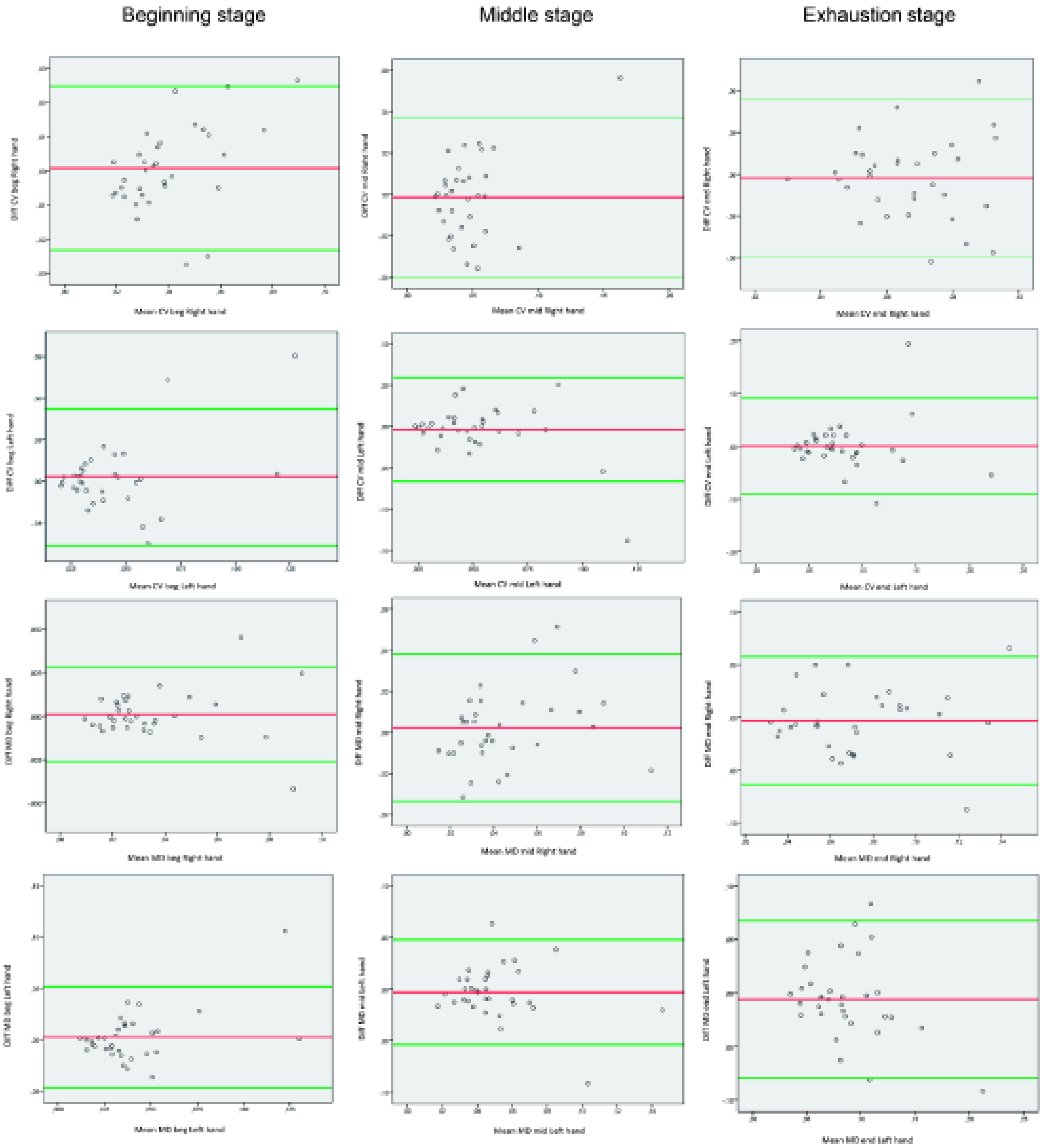

Table 1. Parameters: test and retest means ± standard deviation, relative and absolute reliability indice

Parameter	**RH**				**LH**			
	Test M±SD	**Retest** M±SD	**ICC**	**SEm**	**Test** M±SD	**Retest** M±SD	**ICC**	**SEm**
MVC (kg)	4.44±1.11	4.44±0.93	.889 (CI .768, .949)	±.338kg	4.04±0.84	3.98±0.90	.914 (CI .819, .960)	±.253kg
TIME (s)	160.1±72.4	151.2±55.2	.810 (CI .625, .910)	±27.8s	156.1±65	154.8±63.5	.837 (CI .668, .923)	±25.7s
CV beg (%)	3.90±2.15	3.91±1.60	.770, (CI .549, .890)	±0.9	4.10±2.39	4.26±2.27	.584 (CI .257, .790)	±1.49
CV mid (%)	4.77±3.37	4.66±2.43	.769 (CI .547, .890)	±1.41	4.96±2.27	5.09±2.31	.567 (CI .232, .781)	±1.49
CV end (%)	6.60±2.37	6.52±2.08	.137 (CI -.274, .499)	±2.05	7.89±3.93	8.23±4.55	.791 (CI .588, .900)	±1.93
MD beg (%)	3.19±2.07	3.19±1.92	.916 (CI .822, .962)	± 0.57	3.47±2.31	3.87±2.32	.756 (CI .532, .882)	±1.14
MD mid (%)	4.48±2.66	4.25±2.32	.782 (CI .573, .896)	±1.15	4.89±2.43	5.03±2.63	.665 (CI .377, .835)	±1.45
MD end (%)	7.08±3.51	7.47±3.39	.561 (CI .228, .776)	±2.27	8.27±3.48	9.19±4.68	.680 (CI .410, .842)	±2.33

Legend. RH: right hand; LH: left hand; M: mean; SD: standard deviation; ICC: intraclass correlation coefficient; CI: 95% confidence interval; SEM: standard error of measurement; MVC: maximal voluntary contraction; CV: coefficient of variability; MD: mean distance; beg: beginning stage; mid: middle stage; end: exhaustion stage

Chapter 2

Force Control in Unimanual and Bimanual Force-Matching Tasks: a Test-Retest Reliability Study.

Article prepared for publication but not submitted

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Force Control in Unimanual and Bimanual Force-Matching Tasks: a Test-Retest Reliability Study.

Abstract

Background: Within- and between-hand coordination are essential to manipulate objects. Despite dexterity has been investigated by many tests, there is a lack of evidence evaluating force control. Therefore, the test-retest reliability of the dynamic contraction (DC) and the bimanual strength coordination (BSC) tasks were investigated in this study to assess within- and between-hand force coordination during pulp-pinch grip.

Methods: 28 healthy people performed the tasks in two sessions spaced one week one from another. DC and BSC consisted of visual-feedback force matching tasks and they were conducted with pinch gauges. DC was a pinch and release task in which participants had to match a force target represented graphically as a square wave. Parameters collected were Mean Distance from the target (MD) and Variability of Force (CV). The task was conducted separately with both hands. BSC required the concurrent use of two strain gauge to measure the simultaneous contraction of both hands exerted to match targets that represented predeterminate combinations of forces between hands. The extracted parameters were MD, CV, and Time required To Reach the targets (TTR). Reliability was assessed in both relative (Intraclass Correlation Coefficient) and absolute terms (Bland-Altman Plot).

Results: In DC, MD and CV showed low-to-good relative reliability in both hands since within-participant and within-group variation were similar. Absolute reliability between sessions was good. MD, CV, and TTR of BSC were good-to-excellent in terms of relative reliability and good consistency.

Conclusion: DC and BSC are reliable tasks to investigate force control within- and between-hands.

Background

Fine manipulation requires high levels of hand motor control to perform movements such as clench, pinch, pick, touch. These movements involve the use of small muscles to move tiny objects within- and between-hands. During a within-hand manipulation (e.g., handwriting), inter-fingers strength coordination is essential to develop a proper force that must be sufficient to prevent the slippage of a holding object between the fingers, but not so strong to break the object and to avoid unnecessary fatigue.

The difference between the exerted force and the minimal force required to hold the object is the so-called "safety margin". This margin is larger in older adults and in several musculoskeletal and neurological disorders.[1–3] An increase of the safety margin seems to be a consequence of the necessity of guaranteeing safer grip when cutaneous sensibility functions or hand afferent signals are compromised.[2,4,5]

Besides altered safety margin, other aspects altering pinch-force control are reported. Blennerhassett et al. (2006) found higher force fluctuations and latency in gripping and lifting objects in stroke patients in the most affected hand.[3] In this study, post-stroke patients had to perform pinch grip-lift and hold tasks and they showed prolonged grip-lift time as well as larger and more variable forces to hold an object compared to the control group (no post-stroke people). Therefore, those force control impairments cause a loss in motor adaptations and force steadiness.[6] Extended time-to-grip objects and increased force variability were also observed in Parkinson's disease[7,8] and cerebellar disorders.[4,9] So that, a wide spectrum of nervous system disorders can compromise hand-force control, causing a loss in manual skills, resulting in high levels of disability. However, because most daily activities (e.g. tying the shoes, opening a bottle, buttoning the shirt) require the collaboration of both hands, also the ability to coordinate upper limbs simultaneously must be preserved.[10] Not only does between-hand manipulation require coordination of both movements and forces exertion between fingers, but it also requires between-hands coordination, involving interhemispheric crosstalk.[11–13] Dysfunctions in the modulation of interhemispheric interactions through corpus callosum, during movement preparation and execution, lead to a decrease in the bimanual performance in terms of both kinematics and kinetics domains.[14–17]

Bimanual movements are analysed by several dexterity tests, such as the bimanual Minnesota Dexterity Test[18] or Tyneside Pegboard Test.[19] Conversely, between-hand force coordination is less investigated. Nevertheless, the ability to produce different pinch submaximal forces with both hands, simultaneously, could represent an interesting outcome in all diseases that affect bimanual coordination. For instance, asymmetry in the total force production was manifested in post-stroke patients during bimanual submaximal force-control tasks, indicating the adoption of different task-specific strategies.[20–22] Precisely, the most affected hand contributed more to total force in a simultaneous bilateral-power grip than in a finger-extension task.[20] Loss in bimanual force coordination was also observed in multiple sclerosis since patients required more time and higher force production to perform bimanual tasks than healthy adults.[23,24] Moreover, in this clinical population, findings suggested a more pronounced deficit in force coordination compared to bimanual movement control.[25]

Hence, reliable tasks, which evaluate within- and between-hand force control, could be deployed in the assessment of the abovementioned disorders. Providing patients with force tasks with visual real-time feedback to investigate the presence of inter-finger and inter-hand force coordination impairments, could be useful in the clinical practice for the proposal of *ad hoc* therapeutic interventions. For this reason, this test-retest reliability study investigated the reproducibility of two tasks aimed at evaluating within- and between-hand force coordination during pinch movements.

Materials And Methods

Study design

A test-retest reliability study of two pinch tasks was developed to assess both within- and between-hand force coordination in a population without any neurological and musculoskeletal disorders. Ethical approval was obtained from the Ethics Committee for University Research of the University of Genova (protocol CERA2020.06). This study was reported according to the Guidelines for Reporting Reliability and Agreement Studies (GRRAS).[26]

Participants

Participants were considered eligible for this study if they were adults over 18 years of age without a history of pain syndromes, injuries, or neurological or musculoskeletal disorders that affected upper limbs. Visual impairments were admitted as long as they could be corrected with optical lenses or spectacles. The sample size calculation was based on a previous calculation performed by Bujang (2017).[27] Therefore, a sample of 22 people should be sufficient to analyse the test-retest reliability. Besides, taking into account a possible 20% of drop-outs, 28 people were enrolled.

Experimental setup

Before starting the protocol, age and handedness, checked with Edinburgh handedness inventory,[28] were collected. All participants provided written informed consent before starting the study. The experiment was conducted by a single physiotherapist, specialised in the rehabilitation of musculoskeletal and rheumatic disorders. Test-retest reliability was performed in two separate sessions, spaced by 7-10 days one from another to reduce possible learning effects. In each session, participants were instructed about the procedure, and a familiarisation trial, consisting in two repetitions of each task, was performed. A measurement instrument (EMAC s.r.l., Genova, Italy), consisting of two pinch gauges (P502.F-S/250N, Deltatech, Forlì-Cesena, Italy) and an amplifier/analog-to-digital converter, was adopted (Figure 1). The system, connected to a PC, measured the force between the index and thumb fingers whilst showing the actual exerted force to the participant through a real-time visual feedback.

Firstly, participants had to perform a pinch MVC twice per hand and the highest values of which were collected to define the target levels of tests.[29] Then, the experimental procedure was made up of two tasks, for both test- and retest-sessions:

- Dynamic Contraction (DC);
- Bimanual Strength Coordination (BSC).

DC is a within-hand force coordination task, in which participants control a cursor by modulating the pinch force in order to match a dynamic force target represented by a square wave of four equal periods. The participants were asked to keep the cursor (graphically represented as a blue point) as close as possible to the force target (red line). Each period consisted of an epoch lasting 3 seconds with 3 seconds of rest, in which the target force was set at 0 kg. The targets of the 4 epochs were set at various %MVC (maximum voluntary contraction) levels from the highest to the lowest ones (i.e., 70%, 40%, 25%, 10%) (Figure 2a).

BSC is a between-hand force coordination task, in which participants, while holding both pinch gauges simultaneously, perform bimanual forces at predefined magnitudes. To perform the BSC task, the Range of Force (RoF) quadrangle needs to be generated with three specific force values. Pinch MVC, measured as the higher value between two trials, was collected in left and right hand independently (L-MVC, R-MVC, respectively) and simultaneously (L+R MVC). The three values are collocated in a Cartesian system in which the x- and y-axis represent right and left strength, respectively. The three points and the value (0,0) constitute the vertices of the RoF quadrangle. Then, the real test can be performed: 12 targets were consecutively and randomly displayed as red points into the RoF polygon. They represented specific combinations of pinch 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) (Figure 2b). Both bimanual symmetric and highly asymmetric force targets were proposed since firsts are performed with relative ease and accuracy error and variability of force increase as the degree of asymmetry increases.[30] Each target was displayed for 5 seconds and separated from each other by 3 seconds of rest. Around each target, a tolerance range of ±10%MVC for both hands was displayed as a light red oval. The force exerted by each participant was displayed as a blue point cursor on the RoF quadrangle. The force exerted with the right and left hand controlled the x-axis and y-axis values, respectively. By modulating the pinch force of both hands independently, 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 (Figure 2c). The sequence of tasks was right-hand DC, left-hand DC, BSC.

Participants’ position was standardised according to the American Society of Hand Therapists' recommendation.[31] Participants were seated in front of a table with shoulder adducted, elbow flexed to 90°, forearm in a neutral position, wrist between 0-30° dorsiflexion and between 0-15° ulnar deviation, thumb and index fingers held the pinch gauge and the three ulnar fingers were clenched (Figure 1). Two soft cylindrical supports with a diameter of 7cm, one for each dynamometer, acted as housing for pinch gauges guarantying the maintenance of the hand position to participants. In unilateral tasks, the no-tested hand was resting on the table, in the bimanual task, the pinch gauges were held simultaneously.

Variables

The variables analysed were Mean Distance (MD) and Coefficient of Variability (CV) for DC task and MD, CV and Time To Reach (TTR) for BSC.

In the DC test, MD_i and CV_i were calculated for each epoch (i=1,2,3,4). The first and the last half-second of each epoch were removed to avoid the effects of the initial force stabilisation and any premature cessation of force production.

MD_i (Eq. 1) was the mean value of the modules of the difference between the participants' delivered force (F_i) and the target force (F_t), normalised by the target force, n_i was the number of force acquisitions.[29] This parameter represents an accuracy index since it defines the mean distance of force from the target.

$$MDi = \frac{\sum|F_i - F_t|}{n_i * F_t} \qquad \text{(Eq. 1)}$$

CV_i (Eq. 2) was the standard deviation of the participants' delivered force (F_i) normalised by the mean force $(\bar{F})$[29,32], representing a pointer of the force variability and, compared to MD, it is independent from the target.

$$CVi = \frac{\sqrt{\frac{\sum(F_i - \bar{F})^2}{n_i}}}{\bar{F}} \quad \text{(Eq. 2)}$$

The mean values of MD $(\frac{\sum_{i=4} MD_i}{4})$ and of CV $\left(\frac{\sum_{i=4} CV_i}{4}\right)$ were collected.

In BSC, MD and CV were at first calculated separately for each hand in each epoch removing the first second. The mean of MD_i and CV_i of 12 epochs (i=1-12) of both hands were calculated, rMD and rCV for right hand and lMD and lCV for left hand. The means between rMDi – lMDi (Eq. 3) and between rCVi – lCVi (Eq. 4) were collected.

$$\text{MD} = \frac{(\frac{\sum_{i=12} rMD_i}{12}) + (\frac{\sum_{i=12} lMD_i}{12})}{2} \quad \text{(Eq. 3)}$$

$$\text{CV} = \frac{(\frac{\sum_{i=12} rCV_i}{12}) + (\frac{\sum_{i=12} lCV_i}{12})}{2} \quad \text{(Eq. 4)}$$

TTR (Eq. 5) was calculated as the time (seconds) needed to enter into the 10%MVC tolerance range (light red oval) as soon as the red target appeared on the monitor. The mean of the 12TTR was collected.

$$\text{TTR} = \frac{\sum_{i=12} TTR_i}{12} \quad \text{(Eq. 5)}$$

Statistical Analysis

Descriptive statistics were carried out to understand the sample's characteristics. Results of parameters of DC and BSC tasks were reported with median, 1 and 3 quartiles.

Measurement agreement between test-retest was assessed through Intraclass Correlation Coefficient (ICC) (two-way mixed-effects, absolute-agreement, single measurement) and Bland-Altman analysis for relative and absolute reliability, respectively.[33–35] Normality was checked by investigation of the kurtosis and skewness indexes and exploration of the Q-Q plot graphs of the dataset. All datasets showed non-Gaussian distribution. To calculate ICCs, the square root of each variable was computed since they followed a similar positive skewness, the new variables showed normal distribution. ICC and its 95% Confidence Interval estimates were interpreted as: <.50 *poor* reliability, between .50-.75 *moderate* reliability, between .75-.90 *good* reliability, >.90 *excellent* reliability.[34]

The differences of each variables, between test and retest, were normally distributed as observed from histogram plots and the related skewness-kurtosis values, a necessary condition for conducting the Bland-Altman analysis.[35] The means and the differences of the pairs of measurements (test-retest) for each participant were displayed in the Bland-Altman plots (B-A plot), one for each variable. Graphically, the mean of the paired observations' difference, the Bland-Altman's 95% limits of agreement (LoA) and their 95% Confidence Intervals (95%CI) were also represented as horizontal lines, in green and red lines, respectively. For the mean difference, the 95%CI was calculated with one-sample t-test. The 95%CI of Upper LoA was identified by $d+c_{0.025}*S_{\mathrm{diff}}$ and $d+c_{0.975}*S_{\mathrm{diff}}$. Lastly, 95%CI of Lower LoA was given by $d-c_{0.975}*S_{\mathrm{diff}}$ and $d-c_{0.025}*S_{\mathrm{diff}}$. d was the mean difference, S_{diff} was the standard deviation of differences and $c_{0.025}$ and $c_{0.975}$ were coefficients reported by Carkeet A (2015) based on degrees of freedom equal to 27.[36]

Results

Twenty-eight people (14 women and 14 men) were enrolled in the study, 4 participants were left-handed. The mean age of the sample and its standard deviation were 42 and 15 years old, respectively, with a range between 18 and 75 years old. Median, 1 and 3 quartiles were summarised in Table 1.

Dynamic contraction in dominant hand

ICC showed *poor-to-good* reliability for MD and *poor-to-moderate* for CV (Table 1). MD and CV B-A plots were reported for dominant hand in Figure 3, with their respective difference of paired measures, lower and upper LoA and 95% Confidence Intervals**.**

Dynamic contraction in the non-dominant hand

On the non-dominant hand, *poor-to-good* reliability was observed for both MD and CV parameters measured by ICCs (Table 1).

Figure 4 shows MD and CV B-A plots of DC and their Mean, Upper and Lower LoA in non-dominant hand.

Bimanual Strength Coordination

All parameters in BSC showed high ICCs, reliability was *moderate-to-excellent* for MD and TTR, while for CV it was *excellent* (Table 1).

B-A plots of MD, CV and TTR variables of BSC were reported in Figure 5.

Discussion

As highlighted by our results, MD and CV in DC in both hands showed lower limits of ICC 95%CIs below 0.5, indicating a *poor-to-good* relative reliability as narrow variance within- and between- participants was found.[33]

In all variables, we observed small interquartile ranges (Table 1) which were similar to the standard deviation of the differences between test-retest (in dominant hand (D) MD=

0.02, CV= 0.03, in non-dominant (ND) hand MD= 0.02, CV= 0.03). Based on those data, the lack of variability among the sample may be a cause of the low ICCs.

Therefore, we calculated the reference ranges (2,5th and 97,5th percentiles) of MD and CV in DC in a healthy population, from a dataset of 338 healthy people extracted from an our previous study.[37] They were D-MD=0.03-0.20, D-CV=0.02-0.22, ND-MD=0.03-0.31, ND-CV=0.03-0.17. The reference ranges gathered from the dataset were extremely larger compared to the scores of participants enrolled in the present study. In line with that, changes between sessions were small and considered clinically irrelevant. Therefore, the relative reliability of MD and CV in DC in both hands can be considered acceptable.

By examining the absolute reliability through B-A plots, we can notice that participants remained within the limits of statistical acceptability and thus did the consistency of values.

Conversely, parameters of BSC showed instead good both relative and absolute reliability (Table 1, Figure 5).

Another finding emerged observing B-A plots was that the mean differences of all parameters were over the zero, indicating that, on average, participants performed better scores in the retest session. The overall practice effect underlies the importance of familiarization processes adopted in the present study to reduce measurement error and to improve repeatability.[38] However, the systematic non-random improvements between sessions were not clinically relevant if they were compared to their respective median values (Table 1) and they did not seem to induce any possible trouble either for clinical implications or research studies.

Hence, we can conclude that pinch DC and BSC tests were reliable in healthy populations. This study was proposed because of the interest in applying the described methodology in pathological contexts to highlight hand impairments of force control in various diseases that affect especially central nervous system,[6,24,39,40] but also other clinical conditions.[41] The DC investigates the ability to coordinate precisely and accurately the force of thumb and index fingers in a unilateral visual-guided force matching task. For this reason, it could be used in diseases in which there is a great variability in force production and difficulty in both planning force execution and reaching specific forces in a reasonable time. Deficits in force variability (CV) and error in matching a target force (MD) are plausible to be found in people affected by many disorders such as stroke [42], Parkinson's disease,[39] cerebellar ones.[43]

Compared to the DC task, the BSC adds a complexity, motivated by the necessity to coordinate the force of both hands simultaneously. This is interesting in problems with planning bimanual movement, feedback correction of force and interlimb force coordination such as after stroke[21] in which abnormalities in interhemispheric interactions are common findings[44], setting thus the basis for investigating the BSC task in people after stroke. Moreover, it could be used in multiple sclerosis since bimanual force coordination seems to be highly impaired[25] and differences in bimanual force may be found also at a subclinical stage of the disease. Lastly, Parkinson's disease and unilateral cerebral palsy are characterized also by mirror movements, consisting of involuntary homologous movements in contralateral hemisoma during voluntary unilateral movements causing difficulty for hands to act independently.[45,46] Likely, bimanual coordination and BSC task may be interfered by mirror movements.[47]

Conclusions

Variables proposed in DC and BSC tasks were reliable in healthy people since they maintain a good consistency. Even if an improvement between test-retest might be generally observed in the variables probably due by a learning effect, it is clinically irrelevant. MD and CV of DC and MD, CV and TTR of BSC need to be investigated through future studies to verify the detection of force control impairments in pathological populations.

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Fig 1. Measurement apparatus

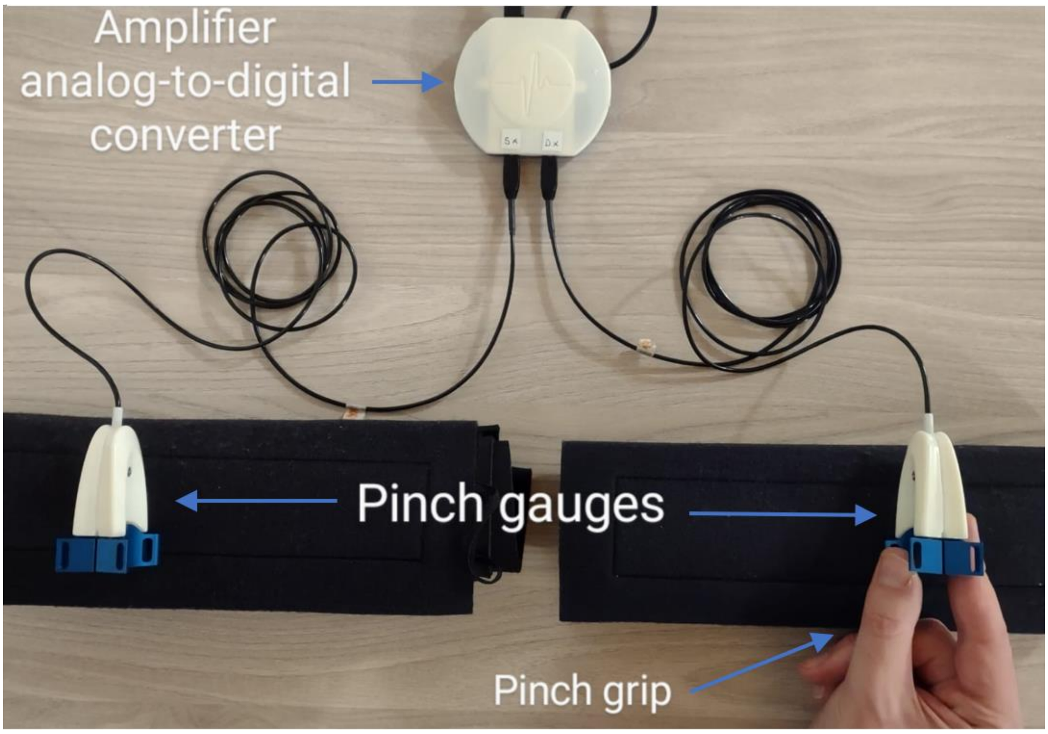


Fig 2. Graphical User Interface of Dynamic Contraction during task (a), Bimanual Strength Coordination, range of force polygon (b) and during the task (c).

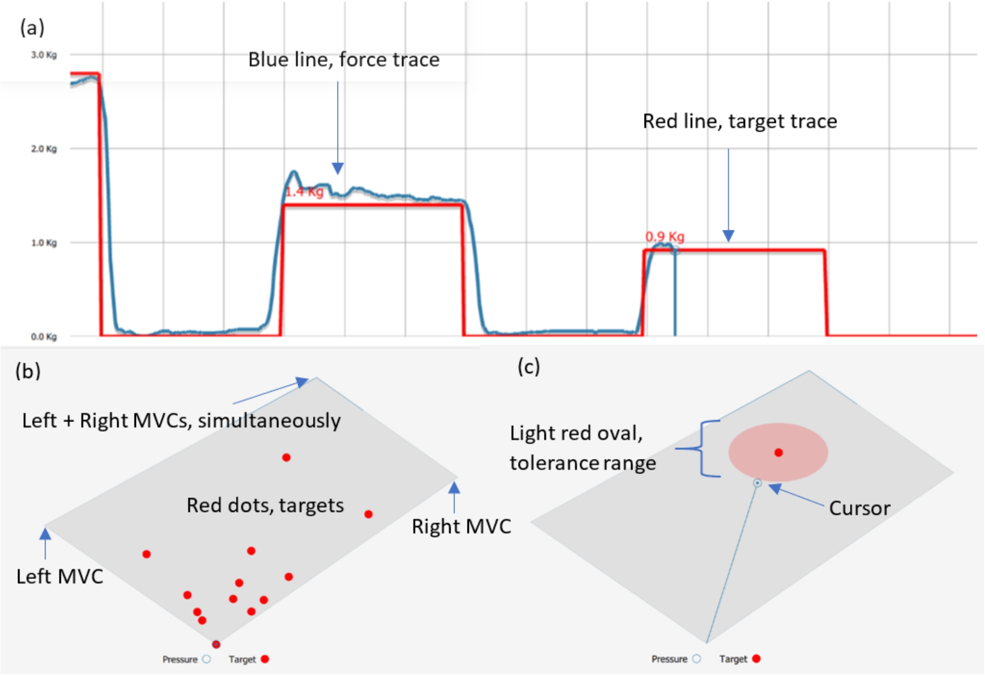
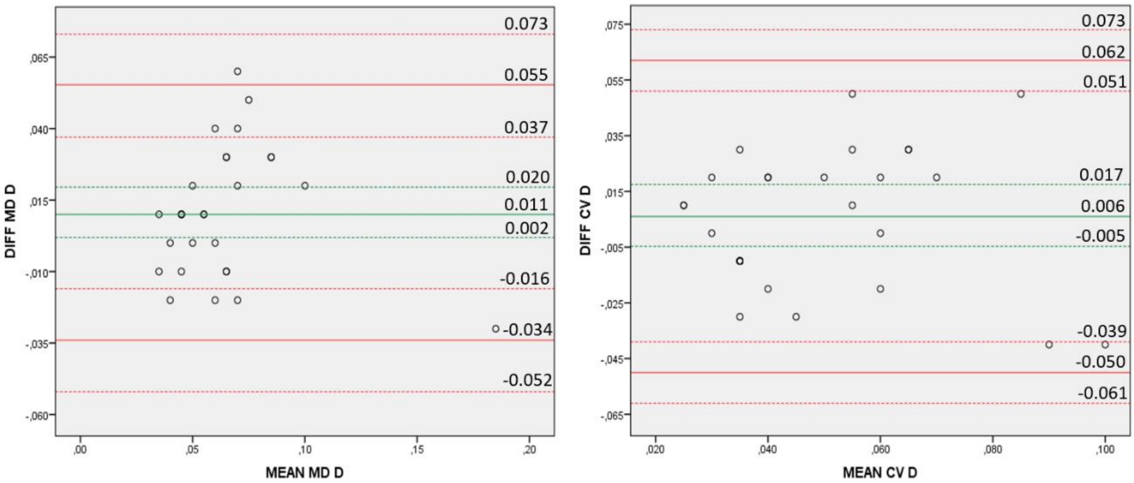
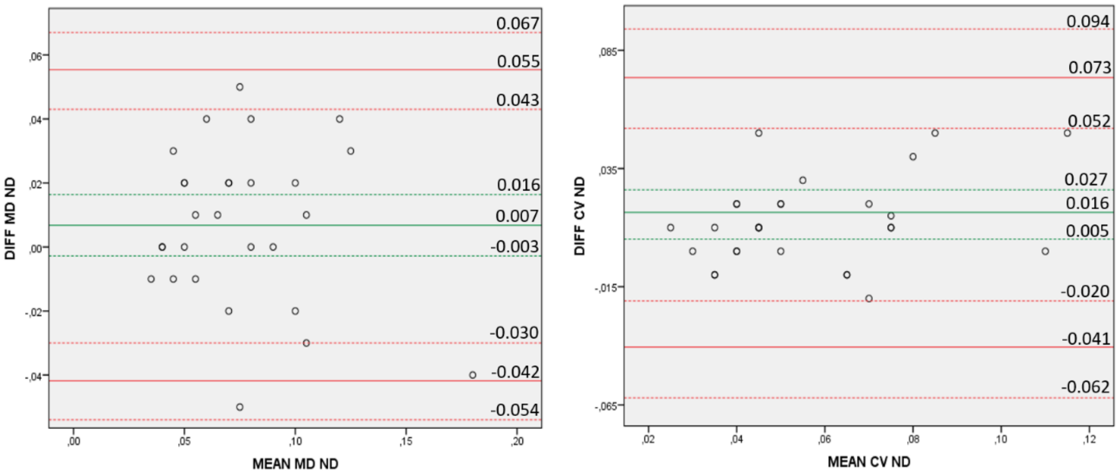


Fig 3. Dynamic contraction in dominant hand: Bland-Altman plots of MD and CV



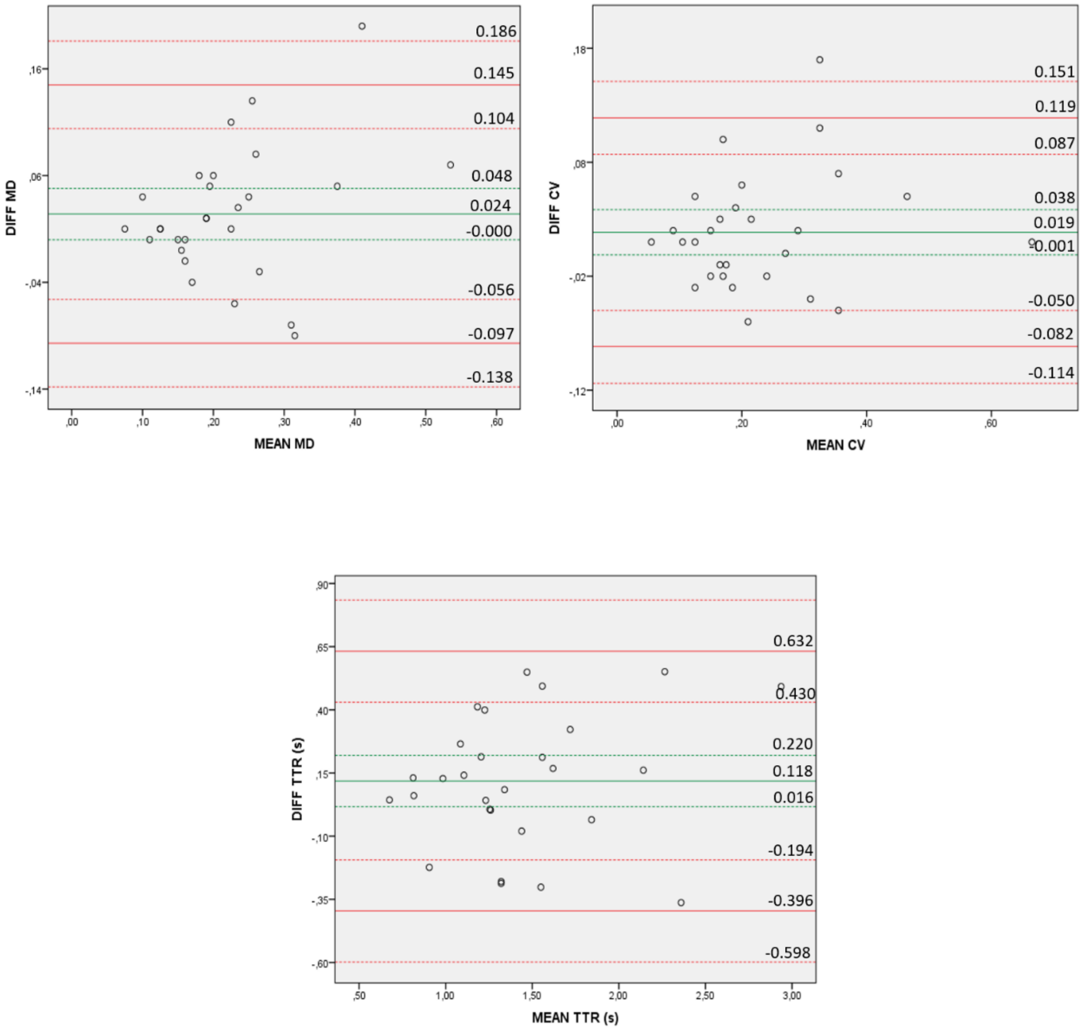
Note: MD, Mean Difference; CV, Coefficient of Variability; Diff, Difference of paired measurements of each participant; Mean, Mean of paired measurements of each participant; D, Dominant hand. The central lines mark the mean difference between test and retest values, and the upper and lower lines represent the 95% Limits of Agreement. Dashed lines are the respective 95% Confidence Intervals.

Fig 4. Dynamic contraction in non-dominant hand: Bland-Altman plots of MD and CV



Note: MD, Mean Difference; CV, Coefficient of Variability; Diff, Difference of paired measurements of each participant; Mean, Mean of paired measurements of each participant; ND, Non-dominant hand. The central lines mark the mean difference between test and retest values, and the upper and lower lines represent the 95% Limits of Agreement. Dashed lines are the respective 95% Confidence Intervals.

Fig 5. Bimanual strength coordination: Bland-Altman plots of MD, CV, and TTR (seconds).



Note: MD, Mean Difference; CV, Coefficient of Variability; TTR, Time-To-Reach; Diff, Difference of paired measurements of each participant; Mean, Mean of paired measurements of each participant; ND, Non-dominant hand. The central lines mark the mean difference between test and retest values, and the upper and lower lines represent the 95% Limits of Agreement. Dashed lines are the respective 95% Confidence Intervals.

Table 1. Results of DC and BSC parameters and their ICC.

	Variable	TEST		RETEST		ICC	[95%CI]
		M	[Q1,Q3]	M	[Q1,Q3]		
D DC	MD	0.06	[0.05,0.08]	0.05	[0.04,0.07]	0.614	[0.30,0.81]
	CV	0.05	[0.03,0.07]	0.04	[0.03,0.05]	0.372	[0.01,0.65]
ND DC	MD	0.08	[0.06,0.09]	0.06	[0.05,0.09]	0.709	[0.47,0.85]
	CV	0.06	[0.05,0.08]	0.04	[0.04,0.06]	0.623	[0.21,0.83]
BSC	MD	0.22	[0.15,0.27]	0.18	[0.16,0.24]	0.831	[0.65,0.92]
	CV	0.20	[0.16,0.29]	0.18	[0.14,0.27]	0.909	[0.81,0.96]
	TTR	1.39	[1.18,1.81]	1.28	[1.02,1.54]	0.856	[0.69,0.93]

Abbreviations: M, median; Q, Quartile; ICC, Intraclass Correlation Coefficient; 95%CI, 95% Confidence Interval; D, Dominant hand; ND, Non-Dominant hand; DC, Dynamic Contraction; BSC, Bimanual Strength Coordination; MD, Mean Distance; CV, Coefficient of Variation; TTR, Time To Reach.

Chapter 3

Flexion-extension Strength of the Index-Thumb System in Italian Population. A Cross-Sectional Study to Gather Normative Data.

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Flexion-extension Strength of the Index-Thumb System in Italian Population. A Cross-Sectional Study to Gather Normative Data.

Abstract

Introduction: Flexion (Palmar Pinch, PP-MVC and Tip Pinch, TP-MVC) and extension (E-MVC) maximal voluntary contraction (MVC) of the index-thumb system offers a quick way to estimate the level of hands' impairment in several musculoskeletal and neurologic conditions.

Purpose of the Study: This study established normative data of PP-MVC, TP-MVC, E-MVC in the Italian population and evaluated their correlation with hand dominance, anthropometric factors, dexterity and workload level.

Methods: In our study, 303 healthy people (150F, 153M) were recruited. Participants performed PP-MVC, TP-MVC and E-MVC tests per hand, conducted by using a pinch-gauge. T-test was used to analyze MVC means between sexes and between hands. One-way ANOVA was conducted to compare MVC means in male and female samples stratified by age (18-29, 30-44, 45-59, 60-74, +75). Spearman's correlation analysis was performed to determine anthropometric variables, dexterity and workload level effects on MVCs.

Results: Medium-to-large effect sizes of age were shown in the majority of tasks. The 30-44y and the +75y age groups showed the highest and the lowest values, respectively, for both sex and both hands. Men were meanly 50% stronger, and the dominant hand showed higher values (6-10%). MVC-tests correlated moderately with weight and height weakly with dexterity and workload level.

Conclusions: After 30-44y, hand strength declines in line with the normal process of aging that also entails muscle fibers and the reduction of daily activities in older adults. In relative terms, E-MVC showed the highest strength loss in the over 75s. The difference between sexes was higher in E-MVC than in flexion MVCs. E-MVC seems to depend more on musculoskeletal architecture that differs from women to men, according to the highest correlation between E-MVC and anthropometric variables. Only high workload levels impacted hand strength. In the heaviest occupations, no PP-MVCs differences were observed between hands.

Introduction

People with hand impairments perceive them as highly disabling since they directly limit activities of daily living[1] or specific professional activities involving hand or thumb.[2]

Pinch maximal voluntary contraction (MVC) offers a quick estimator of the level of hand impairment and disability.[3–8] Thus, normative data of pinch MVC represent a useful comparator to monitor the evolution of prehension-related disorders in different musculoskeletal and neurological conditions and to set the outcome level that should be reached in both hand surgery and rehabilitation.[9–13]

The opposite of the pinch grip is a complex movement that consists of performing the abduction of the thumb while the index extends away from the thumb simultaneously. It involves many muscles that contribute to the first carpometacarpal joint stability, such as the abductor pollicis longus, the extensor pollicis longus and brevis, and the first dorsal interosseus (FDI)[14–17]. The maximal force expressed during the opening of the pinch, extension MVC (E-MVC) could be another important outcome measure to assess the hand functionality in several different conditions. Villafañe and Valdes revealed that E-MVC was lower in people with first carpometacarpal osteoarthritis compared to the healthy population.[18] E-MVC could be influenced by peripheral neuropathies, such as carpal tunnel syndrome, since median nerve block causes a loss in thumb abduction strength,[19,20] and by de Quervain’s syndrome, people affected by the aforesaid tenosynovitis showed low MVC values in extension and abduction of the thumb.[21,22]

As suggested by Ügurlu and Özdogan,[10] the MVC is influenced by habits, culture and anthropometric factors, so that every population should have its own reference data.

Currently, no normative data of pinch MVC are available for the Italian population, and E-MVC reference values have never been previously investigated.

The purpose of this study is to establish normative data in an Italian population of MVC of palmar (PP), tip (TP) pinches and E-MVC. Moreover, correlations of PP, TP and E-MVCs with age, sex, body mass index (BMI), work demand and dexterity are analyzed.

Materials And Methods

Study Design

A cross-sectional design study was developed, aimed at establishing normative data on pinch and extension MVC of the thumb and index finger system. This study was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[23]

Participants

We considered eligible for this study, adult people (aged ≥18) without any musculoskeletal or neurological disorders, acute pain or functional restrictions that could impact upper limbs strength. We excluded people that had been hospitalized in the previous six months before the experimental session (i.e., heart attack or any surgery).[9,24]

People unable to understand the tasks or with visual restrictions that could jeopardize the view of the computer monitor were not considered eligible, the use of spectacles or contact lenses was allowed. According to Werle, we excluded mixed-handed.[25] Participants were required to refrain from caffeinated or alcoholic beverages in the six hours prior to start the session. The participants were recruited between June and September 2020. No follow-up recordings were conducted.

Informed consent was obtained from participants before starting the experimental protocol.

The study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee for University Research, University of Genoa (approval date: 10/06/2020; CERA2020.06).

Measurement system and procedure

The MVCs of each participant were collected by a trained physiotherapist through a standardized procedure. A novel pinch gauge (EMAC s.r.l., Genova, Italy) (Figure 1) was adopted, thanks to its ergonomic and versatile mechanical design, the device can be used to record both compression and traction (E-MVC). The system consists of a load cell (P502.F-S/250N, Deltatech, Forlì-Cesena, Italy), with a measuring range of ±250N and a nominal sensitivity of 2,880 ± 0,150 mV/V, a strain gauge amplifier, a Wheatstone Bridge circuit that determines the relative changes in electric resistance of the two sensors, and the analogue-to-digital converter that digitalized the input signal. The device is connected to the PC via USB since it associated with a software, created *ad-hoc* from one previously adopted for research in motor control.[26–28] A friendly user graphical interface (GUI) provides to participants real-time visual feedback of exerted force and analyses data.

The participants' position was standardized according to the American Society of Hand Therapists (ASHT) recommendations.[29] Participants seated on a chair with feet laid on the floor, shoulders in a neutral position, arms parallel to the trunk, elbow flexed at 110°-150° without any component of supination, forearm resting on the table, the wrist in neutral position (0-15° of extension and 0-15° ulnar deviation) (Figure 2).[9] A computer screen was positioned at 85 cm in front of the participant, providing them with the GUI, showing the visual feedback (VF) of the pinch gauge.

The experimental MVC protocol consisted of three tests per hand:

- *Palmar pinch MVC (PP-MVC),* the pinch gauge was taken by using the thumb and index fingertips parallel and with the remaining fingers clenched (Figure 3a);
- *Tip pinch MVC (TP-MVC)*, here, the pinch gauge was taken with the thumb and index fingertips forming a circle, the interphalangeal (IP) joints had to remain in flexion position and no IP extension was admitted. The remaining fingers were clenched. In both tasks, the participants had to squeeze the pinch pads as hard as possible (Figure 3b);
- *Extension MVC (E-MVC*), in which two Velcro straps were added to the device surrounding the thumb at nail fold level and the distal-interphalangeal (DIP) of the index. The pinch gauge was taken by using the thumb and index fingertips, parallel and with the remaining fingers extended. The task is the opposite movement of pinch and required participants to pull the thumb and the index apart as hard as possible (Figure 3c).

During the three tests, the unassessed hand had to lay on the table.

The GUI provided the participants with real-time VF showing the exerted weight force expressed in kilograms (Figure 1c). Before starting with the experimental protocol, the measurement system was calibrated and the procedure was explained to the participants. Then, a familiarization phase, in which the participants had to perform the three tests with both hands, was performed to get them acquainted with the device.

Each participant was tested two successive times for each task, and the maximum value was recorded and included in the analysis.[30]

The order of the tests and of which hands to start with was randomly selected by an ad-hoc formula created in Excel. A cool-down phase lasting one minute was inserted between each test.

Variables

PP-MVC, TP-MVC and E-MVC were assessed as primary variables. The secondary variables evaluated were sex (F/M), age (years), weight (Kg), height (cm), body mass index (BMI), hand dominance (right/left), dexterity and workload. By the Italian version[31] of the Handedness Edinburgh Inventory (HEI)[32] we identified dominant (DH) and non-dominant (NDH) hands to avoid bias, being left-handed people about 10% of the population.[33] HEI defines the hand-dominance based on the chosen hand to perform different activities, and its score ranges between a laterality quotient of ±100 points. Participants were considered right-handed if the score ranged from 61 to 100, left-handed from -100 to -61 and mixed-handed from -60 to 60.

The manual dexterity was assessed through the Rolyan® 9 Hole Peg Test (9HPT) since it is commonly used in research and clinical practice, and it can carry out a reliable measure.[34] Instruction and demonstration were given in according to Mathiowetz.[35] Participants had to perform a familiarization phase of the test. After that, the real timed test started when the participant took the first peg and stopped when the last one touched the board. The order of the hand to start with was randomized.

The workload was assessed through the Dictionary of Occupational Titles (DOT).[36] It is an occupations' register in which the worker must be matched with the occupation title that better describes their daily work. DOT classifies titles in five groups: sedentary (S), light (L), medium (M), heavy (H) and very heavy (VH). Since students, unemployed, pensioners and homemakers are not classified in the DOT, they were taken into account as follows[25]: the housewife was defined as a medium-grade job (M) whereas students, unemployed, and pensioners were considered as sedentary occupations (S).

Study Size

A *priori* analysis was run with G*Power 3.1 to calculate the sample size. Based on One-way ANOVA, a sample of 300 participants was determined to accept a power of 95% a significant level of 0.05 and an effect size of 0.25.[37]

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 the primary outcomes were normally distributed in both age and DOT categories groups and were analyzed with parametric tests. Instead, the secondary outcomes did not follow a normal distribution and were analyzed with non-parametric tests. Descriptive statistics were carried out to understand the sample’s characteristics. Values that exceed three standard deviations were considered outliers and excluded. Participants were divided into five age groups: 18-29y, 30-44y, 45-59y, 60-74y, +75y.

Between Age-Groups Analysis

One-way ANOVA and its respective post-hoc tests (Tuckey and Gabriel), were conducted to compare MVC means among women and men age groups. Tuckey post-hoc test was conducted to compare MVC means among women since each age group accounted for the same sample size. Conversely, Gabriel post-hoc test was used among men since the different age groups were unbalanced concerning the sample size. The main effects of the overall comparison between groups was reported as eta-squared (η^2), following Cohen's guidelines: .01 small, .059 medium, >.138 large.[38] Moreover, mean differences (MDs) together with their 95% Confidence interval (95% CI) were reported for each significant comparison.

Between Sex Analysis

The Independent Samples T-test was used to compare MVC means of the men and women in each age group. MDs together with their 95% CIs were reported for each comparison.

Between Hand-Dominance Analysis

The Independent Samples T-test was used to compare MVC means of dominant and non-dominant hand in each age group. MDs together with their 95% CIs were reported for each comparison.

MVC Differences Between Hands and Workload

Since not only does hand strength depend on hand dominance, it also depends on the activity level, so that we expected that strength difference between hands reduced as the workload level increased. One-way ANOVA, with Gabriel post-hoc test, was conducted to compare MVC difference between hands (DH and NDH), and DOT categories. The effect size of each comparison was measured through eta-squared (η^2). MDs together with their 95% CIs were reported for each significant comparison.

Correlation Analysis

Spearman's correlation analysis was performed to investigate the correlations between the different MVC tests and the anthropometric characteristics of the sample, the dexterity, and the workload levels. The correlation strength was defined as very-high ($\rho > 0.9$), high ($\rho = 0.7$–0.89), moderate ($\rho = 0.5$–0.69), low ($\rho = 0.3$–0.49), or very low ($\rho < 0.29$).[39]

Multiple Regression Analysis

Finally, the relationship between the secondary and primary variables was analyzed through several multiple regressions with backward deletion method. The effects/relationships of the secondary variables were explored in a preliminary step. The secondary variables that did not meet multiple regression assumptions, were excluded from the analysis. Hence, height and weight were not included in the regression as they showed a high correlation with sex. 9HPT and DOT were not included because of their low correlation with pinch strength. All the included variables respected the assumptions of multivariate normality, of no multicollinearity and of homoscedasticity. Therefore, six multiple regressions were proposed, one for each MVC task (TP-, PP-, E-MVC) of each hand, that were considered as dependent variables, whilst, the independent variables consisted in sex, age, and BMI. The R^2 was calculated to explain the overall model fit.

Results

In line with the eligibility criteria, three hundred and four participants (150 women, 154 men) joined the study, one outlier was found and excluded from the analysis. Five age groups per sex were identified, consisting of 30 participants, except the 30-44y male subgroup, in which the normality of dataset distribution was reached at 33 subjects.

Table 1 reports the descriptive characteristics of the investigated sample. Table 2 and Figs. 1-3 report the performances in the subgroups of TP-MVC, PP-MVC, E-MVC.

Between Age-Groups Analysis

As highlighted by the 95% CIs and by the reported effect sizes, all tests showed significant main effect, in both sexes, except for PP-MVC in women in dominant hand (Table 3). Effect sizes spaced from medium (TP-, PP-MVC tasks) to large (E-MVC tasks). Generally, 30-44y subgroup showed highest MVCs values, on the contrary +75y participants were the weakest. As consequence, post-hoc analysis detected significant difference mainly between those age groups, their mean difference was at least of .700kg in TP and PP MVCs and more than .300kg in E-MVCs in both sexes (Table 3).

Between Sex Analysis

The between-sex analysis indicated a significant difference between men and women groups, in all the MVC tests, for both dominant and non-dominant hand, in all the different age subgroups, as reported by the 95% CIs (Table 4). In percentage the difference between women and men was between 51% and 58% in TP and PP MVCs, 71% in DH and 77% NDH respectively in E-MVC.

Between Hand-Dominance Analysis

Regarding the between hand-dominance analysis, in female sample, we found a significant difference between the dominant and non-dominant hands, in the PP-MVC test for the 45-59 y group (t(58)=2.18, p<.05, Mean Difference, MD=0.45kg, 95%CI [0.04-0.85]), in the TP-MVC test and in the PP-MVC test for the 60-74y group (t(58)=2.60, p<.05, MD=0.44kg, 95%CI [0.10-0.79]; t(58)=2.17, p<.05, MD=0.38kg, 95%CI [0.03-0.74] respectively). Instead, in men, a significant difference was found in the PP-MVC test for the 18-29y group (t(58)=2.78, p<.01, MD=0.73kg, 95%CI [0.2-1.25]), for the 60-74y (t(58)=2.02, p<.001, MD=0.57kg, 95%CI [0.00-1.13]) group and TP-MVC test in the over 75y group (t(58)=2.12, p<.05, MD=0.62kg, 95%CI [0.04-1.21]). Finally, in the E-MVC tests, significant difference was not reached in any age group.

MVC Differences Between Hands and Workload

We compared inter-hand strength difference between different DOT categories, observing significant main effect in PP-MVC test: strength difference in H category was lower than in S, L, M categories (see Table 5, Figure 7). No significant difference was observed in TP- and E-MVC tests.

Correlation Analysis

All correlation coefficients, as well as their statistical significance, are reported in Table 6. *High* correlations were found between TP-MVC and PP-MVC tests in both dominant and non-dominant hands, *moderate-to-high* correlations of E-MVCs emerged with pinch MVC tests.

The inter-hands analysis showed that the highest correlations were those between the same paired tests (Table 6)

The MVCs values correlated *moderately* with weight and height, *low-to-very low* with BMI, age (negatively) and DOT. Finally, no correlations were found between the tests and the 9HPT (Table 6).

Multiple Regression Analysis

Multiple regressions were run to predict PP-, TP-, E-MVC values in both DH and NDH from sex, age, BMI. All three variables added a statistical significance to all predictions ($p < .05$), sex was the higher predictor, followed by BMI and, finally, by age. In all regressions, the overall model fit showed R^2 higher than 0.46. Regression coefficients and standard errors can be found in Table 7.

Discussion

Although changes in strength were generally not significant between contiguous age groups (Table 3), a curvilinear relationship between strength and age emerged from our results, in line with the previous findings regarding both pinch MVC[25,40,41] and anthropometric factors.[42–46] Initially, strength grows probably because of the maturation in the biological functions, physical performance, anthropometric factors and lifestyle and after 30-45 years the curve gradually declines accordingly with physiological modifications by ageing such as the loss in number and size of muscle fibres, especially type-II fibres,[43,45] the changes in muscle architecture[46] and in the neural system,[42,44] with a progressive and accelerated muscle and strength loss which reaches its peak, according to our results, at the seventh decade.

The relationships between MVC and age were similar between Tip and Palmar pinch (Table 2, Figures 4, 5), whereas E-MVC showed higher decline in muscle strength as the age increasing (Table 2, Figure 6), confirming the strongest negative association between age and this parameter (Table 6). Difference between pinch MVCs and E-MVC could be explained since the latter is not part of daily movement repertoire and the lesser muscle activity of extensor compartment can result in a premature muscle loss. Strengthening and inactivity are fundamental factors in the muscle loss due by ageing.[47,48]

Our data showed lower values of tip pinch MVC means in relation to age, in both sexes compared to previous studies.[10,40,49,50] Normative data established by Puh showed values even twice as high as ours.[40] Those differences could be due to various factors. Anthropometric differences and habits beneath populations are probably responsible for these strength differences. Jeune et al., for example, collected handgrip strength in Danish, French and Italian old adults sample and they found a clinically and statistically significative reduction in strength based on the latitude where the data were collected, showing a northern-to-southern negative gradient.[51] However, this can also be due to the fact that in our study we explained the participants to pinch only with the tips of thumb and index fingers and no hyperextension of DIP or proximal pulp contact with the strain gauge were allowed. This was done to allow for studying with greater precision the strength of the thumb-index system without possible compensation from other muscles of the hand. In fact, this setting was not well described in previous research, but the impossibility of extending the index interphalangeal, and the need for a major motor control to avoid this movement to happen, may have reduced maximal strength scores among our sample.

The posture and the position of upper limb modify the maximal strength during squeezing. In particular, it was shown that the positions of elbow, forearm,[52] wrist[53] and ulnar three fingers[54] influence the pinch strength. However, posture is not relevant to explain strength difference between studies since it was mostly standardized and similar across studies, even if not all ones specificized if the ulnar three fingers were flexed or extended.

The difference could also be due to the difference between the measurement systems used in the different studies. However, the pinch gauge used in the present study was validated in laboratory and differences in thickness of instrumentation should be irrelevant in pinch strength if they are between 2.0 and 4.4 cm.[55]

Lastly, MVC is also correlated to the level of verbal encouragement given by the rater,[56,57] in this study we informed people to squeeze the pinch, but no type of verbal reinforcement was given during the task. Many aspects may contribute to the variation of the detected MVC, for this reason we recommended to standardize setting, procedure, posture and the verbal information we provide the person with.

Regarding the sex differences, men showed significantly higher strength compared to the women in each age- and hand-subgroup at the three tests as reported in previous findings.[9,58,59] Sex differences of MVC values were similar between DH and NDH. These differences were mainly due to the anthropometric and body composition differences that characterized the sexes.[60] The difference between the two sexes seems to grow up until 60-74y subgroup. Because of the higher age-related strength loss in men than women between 60-74y and +75y, the percentage difference between the two sexes decreases, as observed in other body districts.[61] Among all tests, E-MVC showed the highest strength difference percentage between sexes in all age subgroups.

As far as the dominance of the hand is concerned, our results showed a 6-10% difference in the tasks between DH and NDH, as highlighted in previous studies.[10,30,40,58]

Strength difference between hands seems also to be influenced by the workload level since PP-MVC difference between dominant and non-dominant hand was lower in the participants classified as “H” in DOT categories compared to “S”, “L”, “M”, according to Josty et al.[62] Even if no significant difference was observed, TP-MVC showed a similar trend to PP-MVC (Figure 7), instead, in E-MVC test the workload level does not seem to influence interlimb strength difference.

Our results suggest that the hand strength depends more on its activity level than on hand dominance, corroborating the opinion of Petersen et al.[63] Observing no strength difference between hands in left-handed people, they assumed that this was due to similar hands usage during everyday activities since left-handed people are often forced to use the right hand.

It might be interesting to indagate if also other parameters of muscle contraction, such as force variability or endurance, are more related to hand use than to hand dominance.

Regarding the correlation analysis, correlations between the MVCs and each anthropometric measure were statistically significant. However, according to previous findings,[10,40,50,64,65] height showed the highest correlation, followed by weight; whereas the lowest correlation was observed in the BMI measure (Table 6). Muscle volume, as well as hand length, are more correlated with height than weight and BMI.[66] Higher muscle volume, and long fingers, which represent an advantageous lever, are able to develop higher strength.[67,68]

In line with Anila et al., our results highlighted that dexterity, evaluated through the 9HPT, and thumb-index system strength seem not to have any relation in the healthy population.[69] Finally, as reported by Ügurlu et al.,[10] we found a low correlation between MVC tests and DOT. However, the low correlation could be due to the fact that DOT category is an ordinal qualitative variable and the size of the difference between categories could be inconsistent.

Based on our results, pinch MVCs and E-MVC are generally superimposable, values showed similar relationship with age and with sex.

However, there are some divergence, E-MVC involves a movement that does not belong to everyday life and for this reason, in our opinion, dominant and non-dominant hands showed similar values and E-MVC showed higher decline with ageing.

Limits of the study

We did not recruit a representative sample of all workload levels, since we found only ten workers classified as H (9 men and 1 woman) and no participants as VH in DOT categories. Based on our results, it could be interesting to investigate in a future study the relationship between workload levels and strength difference between DH and NDH, recruiting a larger sample of heavier occupations, because those findings would highlight the fact that people employed in different jobs require different rehabilitative outcomes.

Conclusions

The present data shows reference values of thumb-index fingers strength for Italian population, adding to pinch MVC also the opposite movement strength, E-MVC. Since E-MVC consists of index extension and thumb abduction, it involves muscles such as abductor pollicis longus and extensors that are not directly involved in pinch grip but that contribute to thumb carpometacarpal active stabilization, representing a further outcome in addition to TP- and PP- MVCs to assess hand function.

Finally, future studies should investigate other parameters of muscle contraction during pinch, such as precision and force variability, in addition to the MCV values. This will allow the clinicians to conduct a complete and proper assessment of the hand motor control in order to provide patients who suffer from hand impairments, with a more personalized care.

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Fig. 1. Hardware (top view) and Graphical User Interface (GUI) of measurement system: a, pinch gauge; b, strain gauge amplifier; c, visual feedback displayed on GUI

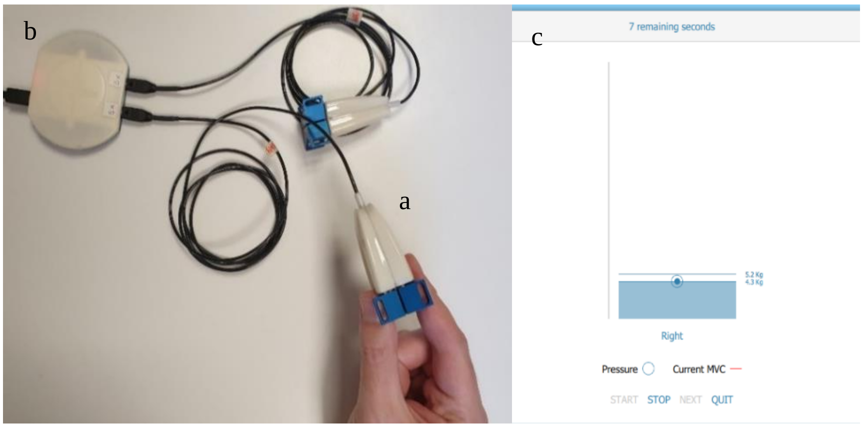

Fig. 2. Experimental setting and participant position: a, pinch gauge; b, strain gauge amplifier; c, smooth surface; d, support for pinch gauge

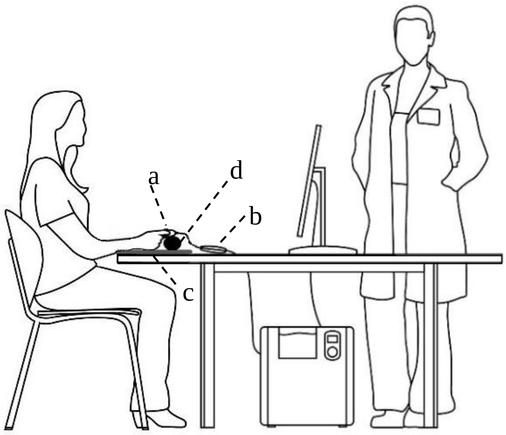

Fig. 3. types of grip during Maximal Voluntary Contractions, from left to right: a) palmar pinch MVC; b) tip pinch MVC; c) extension MVC

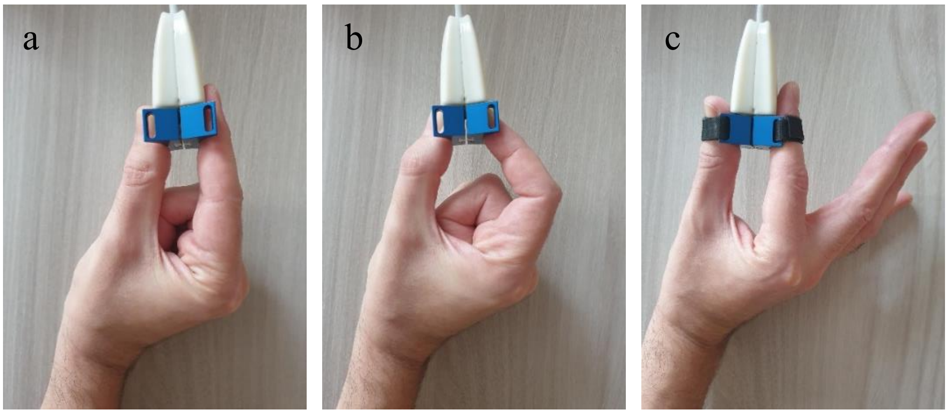

Fig. 4. Comparison of Tip Pinch Maximal Voluntary Contraction between age groups and between sexes

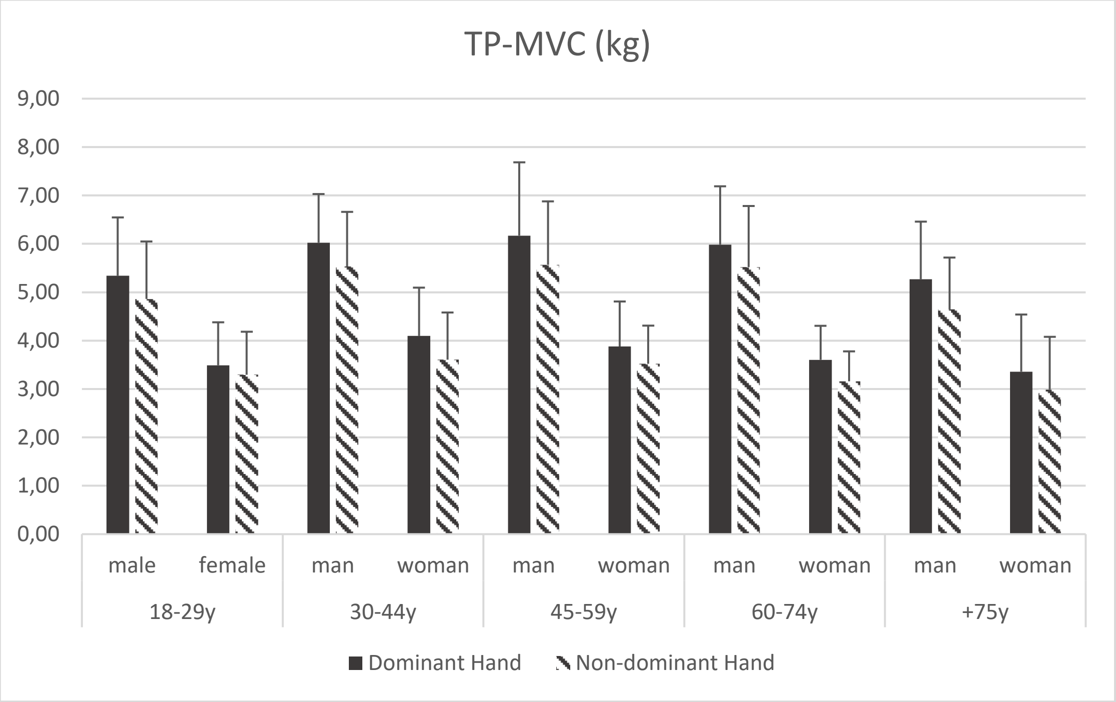

Fig. 5. Comparison of Palmar Pinch Maximal Voluntary Contraction between age groups and between sexes

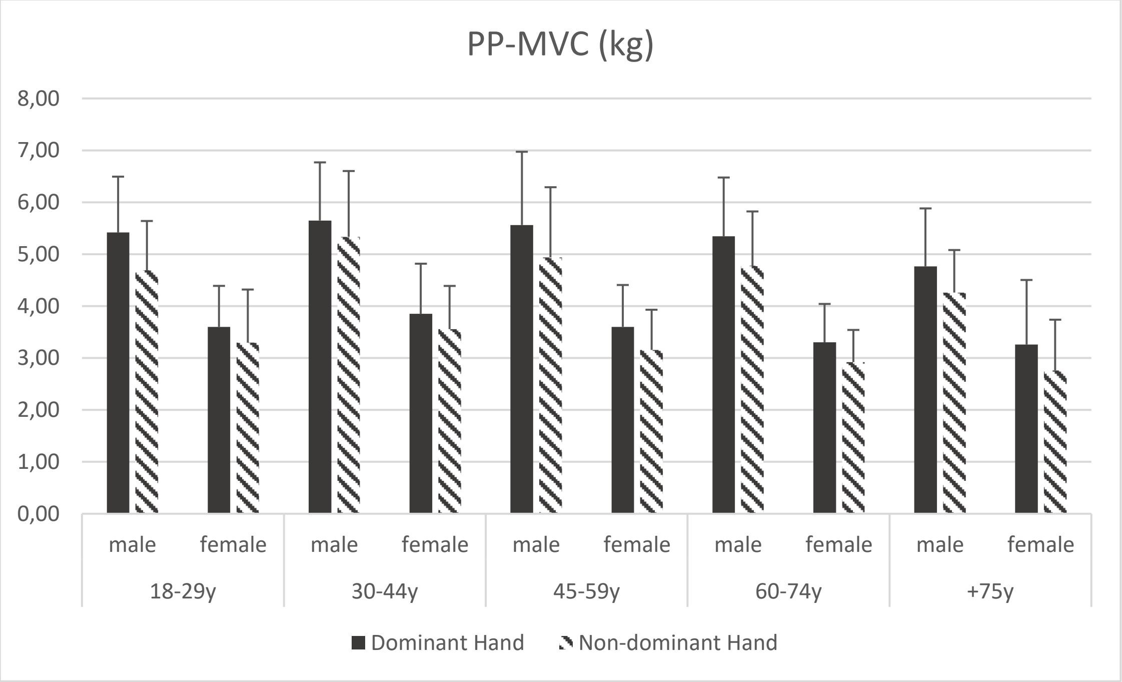

Fig. 6. Comparison of Extension Maximal Voluntary Contraction between age groups and between sexes

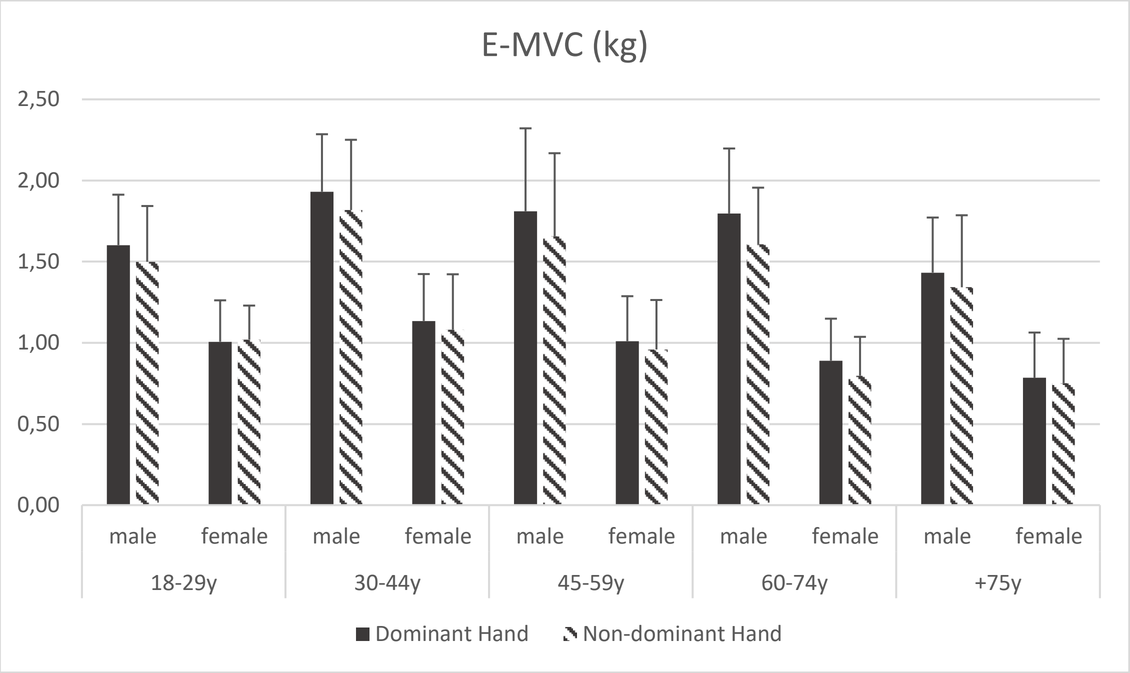

Fig. 7. From left to right PP, TP, E MVCs difference between dominant and non-dominant hand, among DOT categories

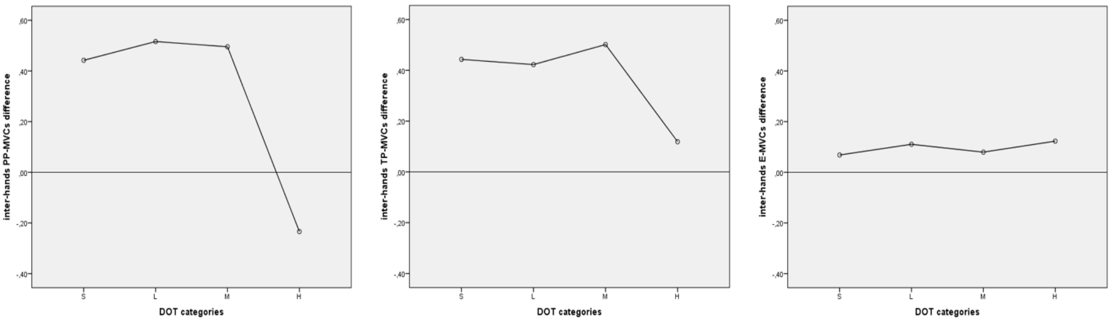

Table 1. Descriptive characteristics of the study sample

			Mean ±SD							**DOT %**			
Age group	**Sex**	**N (outliers)**	**Age (y)**	**RH:LH**	**Height (m)**	**Weight (kg)**	**BMI**	**9HPT DH (s)**	**9HPT NDH (s)**	S	L	M	H
18-29Y	♀	30 (0)	24.4±3.2	27:3	1.66±0.07	60.8±13.2	21.9±3.37	17.7±2.3	19.5±2.4	40%	36.7%	23.3%	0%
	♂	30 (0)	24.9±3.04	27:3	1.78±0.05	73.5±7.3	23.28±1.84	18.5±1.9	19.9±1.5	20%	16.7%	63.3%	0%
30-44Y	♀	30 (0)	37±5.07	27:3	1.64±0.06	57.5±8.4	21.45±2.71	17.4±1.8	18.8±2	10%	56.7%	33.3%	0%
	♂	33 (0)	35.5±4.45	29:4	1.79±0.06	80.5±13.9	25.11±3.67	18.2±2.4	20.1±3.3	10%	46.7%	40%	13.3%
45-59Y	♀	30 (0)	52.8±4.3	28:2	1.64±0.06	64.4±13.6	23.8±4.28	18.2±2.8	19.7±2.3	3.3%	50%	46.7%	0%
	♂	31 (1)	52.3±4.3	24:7	1.77±0.06	79.6±11.3	25.3±2.8	18.8±2.4	20.9±3	10%	56,7%	30 %	3.3%
60-74Y	♀	30 (0)	66.7±4.41	28:2	1.6±0.05	69.6±14.8	27.19±5.87	21±4.1	22.2±3.9	36.7%	20%	40%	0%
	♂	30 (0)	65.9±4.14	27:3	1.75±0.08	85.5±12.9	27.71±3.26	22.6±3.9	23.6±3.7	40%	43.3%	6.7%	6.7%
+75Y	♀	30 (0)	79.8±3.9	30:0	1.6±0.05	66.9±11.1	26±3,49	25.3±5.1	27.1±5.7	86.7%	0%	6.7%	3.3%
	♂	30 (0)	79±4.2	30:0	1.73±0.06	79.1±12.6	26.37±3.23	25.8±5.3	27±4.7	83.3%	3.3%	3.3%	6.7%

Legend: SD, Standard Deviation; RH, Right hand; LH, Left hand; DH, Dominant hand; NDH, Non-dominant hand; BMI, Body mass index; 9HPT, 9 Hole Peg Test; DOT, Dictionary of Occupational Titles; S, Sedentary; L, Light; M, Medium; H, High; ♀, Women; ♂, Men.

Table 2. Normative values of Tip, Palmar Pinch, and Extension MVCs, values are expressed in Kilograms

		DH						**NDH**					
		TP-MVC		**PP-MVC**		**E-MVC**		**TP-MVC**		**PP-MVC**		**E-MVC**	
Age groups	**Sex**	X̄	SD	X̄	SD	X̄	SD	X̄	SD	X̄	SD	X̄	SD
18-29Y	♀	3.49	.76	3.60	.79	1.01	.26	3.29	.89	3.30	.70	1.02	.21
	♂	5.34	1.21	5.42	1.08	1.60	.31	4.86	1.19	4.69	.95	1.50	.34
30-44Y	♀	4.10	1.00	3.85	.96	1.14	.29	3.61	.97	3.56	.83	1.08	.34
	♂	6.02	1.01	5.65	1.12	1.93	.35	5.53	1.13	5.33	1.27	1.82	.43
45-59Y	♀	3.88	.93	3.60	.81	1.01	.28	3.52	.79	3.16	.77	.96	.30
	♂	6.01	1.26	5.39	1.08	1.77	.46	5.50	1.27	4.83	1.21	1.61	.43
60-74Y	♀	3.60	.70	3.30	.74	.89	.26	3.16	.62	2.92	.62	.80	.24
	♂	5.98	1.21	5.34	1.13	1.80	.40	5.52	1.26	4.78	1.05	1.61	.35
+75Y	♀	3.36	1.18	3.26	1.24	.78	.28	2.99	1.09	2.76	.98	.75	.27
	♂	5.27	1.19	4.76	1.12	1.43	.34	4.64	1.07	4.26	.82	1.34	.44
Total	♀	3.69	.96	3.52	.94	.97	.29	3.31	.90	3.14	.83	.92	.30
	♂	5.73	1.21	5.32	1.13	1.71	.41	5.22	1.23	4.79	1.12	1.58	.43

Legend: DH, Dominant hand; NDH, Non-dominant hand; MVC, Maximal voluntary contraction; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; ♀, Women; ♂, Men; X̄, Mean; SD, Standard deviation

Table 3. One-way ANOVA and post-hoc tests for the main effect of age groups in Palmar Pinch, Tip Pinch, and Extension MVCs.

Part 1		**Main effect,** η^2	**Post-hoc tests,** mean difference (kg) [95%CI]				
		Age	18-29 vs 30-44	18-29 vs 45-59	18-29 vs 60-74	18-29 vs +75	30-44 vs 45-59
Hand	Task	♀					
DH	**PP**	.054	N.P.	N.P.	N.P.	N.P.	N.P.
	TP	.079*	-0.61 [-1.27-0.06]	-0.39 [-1.05-0.28]	-0.11 [-0.78-0.55]	0.13 [-0.53-0.8]	0.22 [-0.44-0.88]
	E	.165**	-0.13 [-0.32-0.07]	0.00 [-0.2-0.19]	0.12 [-0.08-0.31]	**0.22*** [0.03-0.42]	0.13 [-0.07-0.32]
NDH	**PP**	.114**	-0.26 [-0.82-0.3]	0.14 [-0.42-0.7]	0.38 [-0.19-0.94]	0.54 [-0.03-1.1]	0.4 [-0.16-0.96]
	TP	.064*	-0.31 [-0.94-0.32]	-0.23 [-0.86-0.41]	0.14 [-0.5-0.77]	0.31 [-0.33-0.94]	0.08 -0.55-0.72]
	E	.179**	-0.06 [-0.26-0.14]	0.06 [-0.13-0.26]	**0.23*** [0.03-0.42]	**0.27**** [0.07-0.47]	0.12 [-0.08-0.32]
		♂					
DH	**PP**	.069*	-0.23 [-1-0.54]	0.02 [-0.76-0.81]	0.07 [-0.71-0.86]	0.65 [-0.14-1.44]	0.26 [-0.51-1.03]
	TP	.082*	-0.68 [-1.5-0.13]	-0.68 [-1.51-0.16]	-0.64 [-1.48-0.19]	0.07 -0.77-0.91]	0.01 -0.81-0.83]
	E	.181**	**-0.33**** [-0.59- -0.07]	-0.16 [-0.43-0.1]	-0.2 [-0.46-0.07]	0.17 [-0.1-0.44]	0.16 [-0.1-0.43]
NDH	**PP**	.097**	-0.64 [-1.39-0.11]	-0.14 [-0.9-0.63]	-0.09 [-0.85-0.68]	0.43 [-0.34-1.2]	0.51 [-0.24-1.26]
	TP	.096**	-0.67 [-1.5-0.16]	-0.64 [-1.49-0.2]	-0.66 [-1.5-0.19]	0.22 [-0.63-1.06]	0.03 [-0.8-0.86]
	E	.137**	**-0.32*** [-0.6--0.04]	-0.11 [-0.39-0.18]	-0.11 [-0.39-0.18]	0.16 [-0.13-0.44]	0.21 [-0.07-0.49]

Part 2

		Post-hoc tests, mean difference (kg) [95%CI]				
		30-44 vs 60-74	30-44 vs +75	45-59 vs 60-74	45-59 vs +75	60-74 vs +75
Hand	Task					
DH	**PP**	N.P.	N.P.	N.P.	N.P.	N.P.
	TP	0.49 [-0.17-1.16]	**0.74*** [0.08-1.4]	0.28 [-0.39-0.94]	0.52 [-0.14-1.18]	0.25 [-0.42-0.91]
	E	**0.25**** [0.05-0.44]	**0.35**** [0.16-0.54]	0.12 [-0.07-0.31]	**0.23*** [0.03-0.42]	0.11 [-0.09-0.3]
NDH	**PP**	**0.64*** [0.07-1.2]	**0.80**** [0.23-1.36]	0.23 [-0.33-0.8]	0.39 [-0.17-0.96]	0.16 [-0.4-0.72]
	TP	0.45 [-0.19-1.08]	0.62 [-0.02-1.25]	0.36 [-0.27-0.99]	0.53 [-0.1-1.17]	0.17 [-0.46-0.8]
	E	**0.28**** [0.09-0.48]	**0.33**** [0.13-0.53]	0.16 [-0.04-0.36]	**0.21*** [0.01-0.4]	0.04 [-0.15-0.24]
DH	**PP**	0.31 [-0.46-1.08]	**0.79*** [0.12-1.66]	0.05 [-0.74-0.84]	0.63 [-0.16-1.42]	0.58 [-0.21-1.37]
	TP	0.04 [-0.78-0.86]	0.76 [-0.06-1.58]	0.03 [-0.81-0.87]	0.75 [-0.09-1.59]	0.72 [-0.12-1.55]
	E	0.13 [-0.13-0.39]	**0.5**** [0.24-0.76]	-0.03 [-0.3-0.24]	**0.33*** [0.07-0.6]	**0.36*** [0.1-0.63]
NDH	**PP**	0.56 [-0.19-1.31]	**1.07**** [0.32-1.82]	0.05 [-0.72-0.82]	0.56 [-0.21-1.33]	0.51 [-0.25-1.28]
	TP	0.01 [-0.81-0.84]	**0.89*** [0.06-1.71]	-0.02 [-0.86-0.83]	**0.86*** [0.01-1.7]	**0.87*** [0.03-1.72]
	E	0.21 [-0.07-0.49]	**0.48**** [0.2-0.76]	-0.00 [-0.29-0.29]	0.26 [-0.02-0.55]	0.26 [-0.02-0.55]

Legend: η^2, eta squared; 95%CI, 95% confidence interval; N.P., No post-hoc test; *, Significant at .05; **, Significant at .01; ♀, Women; ♂, Men; DH, Dominant hand; NDH, Non-dominant hand; MVC, Maximal voluntary contraction; TP, Tip Pinch; PP, Palmar Pinch; E, Extension.

Table 4. Independent Samples T-tests of MVCs differences between sexes in each age group

	t-value(df), p-value **Mean Difference (Kg), [95%CI]**					
Age groups	**DH**			**NDH**		
	TP-MVC	**PP-MVC**	**E-MVC**	**TP-MVC**	**PP-MVC**	**E-MVC**
18-29Y	t(58) =7,1, p<.0001, MD= 1.85; [1.33-2.37]	t(58) =7,46, p<.0001, MD= 1.82; [1.33-2.31]	t(56) =8,11, p<.0001, MD= 0.6; [0.45-0.74]	t(58) =5,78, p<.0001, MD= 1.57; [1.02-2.11]	t(53) =6,47, p<.0001, MD= 1.39; [0.96-1.83]	t(58) =6,48, p<.0001, MD= 0.48; [0.33-0.62]
30-44Y	t(61) =7,62, p<.0001, MD= 1.93; [1.42-2.43]	t(61) =6,84, p<.0001, MD= 1.8; [1.27-2.32]	t(60) =9,81, p<.0001, MD= 0.8; [0.63-0.96]	t(61) =7,26, p<.0001, MD= 1.93; [1.4-2.46]	t(61) =6,5, p<.0001, MD= 1.78; [1.23-2.32]	t(60) =7,55, p<.0001, MD= 0.74; [0.54-0.93]
45-59Y	t(53) =7,46, p<.0001, MD= 2.14; [1.56-2.71]	t(58) =7,3, p<.0001, MD= 1.79; [1.3-2.29]	t(58) =7,76, p<.0001, MD= 0.76; [0.56-0.95]	t(48) =7,26, p<.0001, MD= 1.98; [1.43-2.53]	t(58) =6,35, p<.0001, MD= 1.67; [1.14-2.2]	t(53) =6,76, p<.0001, MD= 0.65; [0.45-0.84]
60-74Y	t(58) =9,33, p<.0001, MD= 2.38; [1.87-2.89]	t(58) =8,26, p<.0001, MD= 2.04; [1.55-2.54]	t(50) =10,43, p<.0001, MD= 0.91; [0.73-1.08]	t(58) =9,19, p<.0001, MD= 2.36; [1.85-2.87]	t(58) =8,34, p<.0001, MD= 1.85; [1.41-2.3]	t(51) =10,47, p<.0001, MD= 0.81; [0.65-0.96]
+75Y	t(58) =6,23, p<.0001, MD= 1.91; [1.3-2.52]	t(57) =4,93, p<.0001, MD= 1.51; [0.89-2.12]	t(56) =8,08, p<.0001, MD= 0.65; [0.49-0.81]	t(58) =5,93, p<.0001, MD= 1.66; [1.1-2.21]	t(56) =6,44, p<.0001, MD= 1.5; [1.03-1.97]	t(48) =6,21, p<.0001, MD= 0.59; [0.4-0.78]

Legend: df, Degree of freedom; DH, Dominant hand; NDH, Non-dominant hand; MVC, Maximal voluntary contraction; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; MD, mean difference; 95%CI, 95% Confidence interval.

Table 5. One-way ANOVA for the effect of the occupational category (DOT classification) in MVCs difference between hands

	Main effect η²	**Post-hoc test**, mean difference [95%CI]					
	DOT	S-H	L-H	M-H	S-L	S-M	L-M
PP-MVCs difference	**0.027***	0.68 [0-1.36]	**0.75*** [0.07-1.43]	**0.73*** [0.04-1.42]	-0.07 [-0.36-0.21]	-0.05 [-0.35-0.24]	0.02 [-0.28-0.32]
TP-MVCs difference	. 0.007	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.
E-MVCs difference	. 0.005	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.

Legend: η², eta squared; 95%CI, 95% confidence interval; *, Significant at .05; N.P., No post-hoc test; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; MVCs, Maximal Voluntary Contractions; DOT, Dictionary of Occupational Titles; S, Sedentary; L, Light; M, Medium; H, Heavy.

Table 6. Spearman's correlation between tasks, hands, age, anthropometric measures, 9 Hole Peg test and Dictionary of Occupational Titles

		DH			**NDH**			**Age**	**Weight**	**Height**	**BMI**	**9HPT**		**DOT**
		TP	**PP**	**E**	**TP**	**PP**	**E**					**DH**	**NDH**	
DH	TP	1.000	**.807****	**.710****	**.843****	**.754****	**.684****	-.064	**.514****	**.594****	**.248****	-.024	.037	**.139***
	PP		.000	**.671****	**.740****	**.807****	**.643****	**-.163****	**.479****	**.598****	**.201****	-.061	-.040	**.155****
	E			1.000	**.721****	**.712****	**.868****	**-.184****	**.514****	**.656****	**.206****	-.077	-.080	**.171****
NDH	TP				1.000	**.796****	**.726****	-.100	**.530****	**.598****	**.261****	-.028	.001	**.156****
	PP					1.000	**.721****	**-.180****	**.493****	**.611****	**.207****	-.049	-.036	**.177****
	E						1.000	**-.227****	**.474****	**.628****	**.172****	-.107	-.107	**.159****

Legend: **, Significant at .01; *, Significant at .05; DH, Dominant hand; NDH, Non-dominant hand; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; BMI, Body mass index; 9HPT, 9 Hole Peg Test; DOT, Dictionary of Occupational Titles.

Table 7. The results of the multiple regression analysis on each MVC task for sex, age and BMI.

			Sex (0=M, 1=F)		**Age (years)**		**BMI**		**Constant**	
	Task (kg)	Adj.R^2	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
DH	**TP-MVC**	.480	-1.972**	.127	-.008*	.003	.046**	.017	6.930	.461
	PP-MVC	.463	-1.724**	.118	-.015**	.003	.041**	.016	6.738	.430
	E-MVC	.559	-.719**	.040	-.006**	.001	.015**	.005	2.336	.146
NDH	**TP-MVC**	.463	-1.809**	.124	-.011**	.003	.059**	.017	6.094	.451
	PP-MVC	.464	-1.562**	.110	-.016**	.003	.051**	.015	5.881	.402
	E-MVC	.494	-.627**	.041	-.006**	.001	.017**	.006	2.108	.151

Legend: **, Significant at .01; *, Significant at .05; SE, Standard Error; DH, Dominant hand; NDH, Non-dominant hand; MVC, Maximal voluntary contraction; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; BMI, Body Mass Index.

Chapter 4

Force control of pinch grip: normative data of a multiparametric evaluation

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as:

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Force control of pinch grip: normative data of a multiparametric evaluation

Abstract

Introduction: Pinch strength is a widely used outcome in hand disorders, but it is not exhaustive in determining impairments of pinch force control.

Methods: Here we gathered normative data by a 328 healthy Italian sample (173W, 163M) of a 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. Kruskal-Wallis and Mann-Whitney U-tests were used to analyze the effect on tasks of age and of sex and hand-dominance, respectively.

Results: SC showed similar values in all age groups, variables of DC and BSC showed instead large effect related to age-decline. Women showed small-to-medium higher scores than men in all tasks, no hand dominance effect emerged in SC and DC. In contrast to an age-related MVC decline, endurance did not change significantly.

Conclusions: Force variability 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 and variability of force of pinch grip in visual-feedback guided task.

Introduction

Pulp pinch Maximal Voluntary Contraction (PP MVC) is an objective outcome, with high test-retest reliability,[1] commonly used in hand injuries to test treatment effectiveness and to monitor the progress of recovery.[2–5]

However, PP MVC cannot be considered an exhaustive parameter of hand function since a low correlation was observed with hand dexterity [6] and with pinch strength control.[7] Moreover, PP is normally considered a precision grip rather than a power one,[8] since people use it to manipulate small objects at various submaximal contractions exerted also for a long time. For this reason, PP MVC cannot be considered the best indicator for a complete analysis of the PP function. The last is influenced not only by muscle strength but also by the integration of sensory input and central processes which aim at developing right force output and coordination both between the fingers and between the hands.[9]

Hence, a more thorough evaluation of PP motor control can act as a precious aid in decision-making, bridging the gap between assessment and treatment of hand impairments. This can be done by introducing a multiparametric evaluation of pinch grip that could require a combination of different representative tests.

Endurance tests are recognised to be useful for the evaluation of both several musculoskeletal disorders [10,11] and for diseases in which fatigue represents a major symptom.[12] Evidence highlights that, during a pinch-release task, the force control was lower in older adults [13,14] and in patients suffering from both cerebellar diseases [15] and neuropathies. [16–18] Therefore, it could be also interesting to evaluate the ability to match and maintain different force levels.[19] Lastly, the pinch is usually used in bimanual tasks and the ability to produce pinch forces at different magnitudes with both hands simultaneously could represent an interesting outcome in all diseases in which coordination between limbs could be affected such as stroke[20] and multiple sclerosis.[21]

In line with this, the present study aims at proposing a new multiparameter assessment of pinch force control, at defining its normative data in the Italian population without life-limiting diseases, and at analysing the correlation of this data with age, sex, dexterity, and hand dominance.

Materials and Methods

Study Design

A cross-sectional design study was developed according to Strengthening the Reporting of Observational Studies in Epidemiology (STROBE).[22] It aimed at establishing normative data of a new multiparameter evaluation of thumb and index motor control in Pulp Pinch (PP) position. This evaluation consisted of performing three different tests: sustained contraction (SC), dynamic contraction (DC) and bimanual strength coordination (BSC). The study was conducted following the Declaration of Helsinki and 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 measurement system (EMAC s.r.l., Genova, Italy) was adopted. It consisted of two digital pinch meters developed ad-hoc, connected to a strain gauge amplifier to convert the signal from analogical to digital. The output signal was sent to the PC via USB and analysed by software which also, through a friendly graphical user interface (GUI), had the function to guide participants and assessor over the tests (Figure 1).[23]

Experimental session

All participants, recruited between June and October 2020, undersigned an informed consent before entering the study. The experimental sessions were conducted by a single assessor, a physiotherapist previously trained in the use of the two physical devices and their related software. People's posture was standardised according to the American Society of Hand Therapists (ASHT) recommendations.[24] 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 with feet on the ground. A PC screen was positioned on the table at 85cm from the participant (Figure 2).

Each participant was instructed about the measurement system, GUI and the posture they had to maintain during the experiment. For the PP configuration people had to take the pinch gauge with thumb and index pads, keeping these fingers straight and parallel, the other fingers were clenched,[25] since pinch strength is influenced by the position of both elbow, wrist, hand and fingers joints.[26,27] As a result, interphalangeal joints are extended, and the thumb is forced to be straight and parallel to the forearm so that the standardised position of the wrist is guaranteed.

Before performing the experimental protocol, participants had to undergo a familiarisation 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 Sustained Contraction (SC), Dynamic Contraction (DC) and Bimanual Strength Coordination (BSC) which respectively indagate 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 randomised by using the random function in Excel. 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 the latter test. Before starting the experimental session, it was necessary to acquire the thumb-index pulp pinch (PP) MVCs of both hands for each participant. The participants had to perform the MVC task twice per hand and the highest values of which were collected to define the target levels of tests (Figure 3).

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 center of a tolerance range identified through two lines (±10%MVC). The force delivered by the participants was displayed as a blue line that raised according to the pressure exerted on the pinch gauge.

The task was automatically interrupted if the delivered force went below the 10% of the SC target-force line for longer than 1 second (Figure 4).

The DC consisted in a force-matching visual feedback-based test, in which 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 (Figure 5). 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.

Finally, BSC test consisted in exertion of in-phase bimanual forces at different magnitudes,[28] using both pinch gauges simultaneously. The first step of this test required the construction of the "Range of Force" (RoF) polygon (Figure 6a). 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 (Figure 6b). 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 BSC test, 12 targets graphically displayed as red points into the RoF polygon, randomly appeared in series, one after the other. They represented both symmetric and highly 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.[29,30] 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 (Figure 6c).

Participants

The participants were over 18, 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.[31] Participants were required to refrain from caffeinated or alcoholic beverages in the six hours prior to start the session.

Variables

Primary Variables

The primary variables of this study are classified according to the test they are extracted from, and they are reported in Table 1.

Time (seconds): the 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%MVC under target force), for more than 1 second.

Mean Distance (MD): it is the mean value of the modules of the difference between the participants' delivered force (F_i) and the target force (F_t), normalised by the target force.[1,32] This parameter represents the accuracy index since it defines the closeness of force to the target.

$$MD = \frac{\sum|F_i - F_t|}{n_i * F_t}$$

Coefficient of Variation (CV): it is the standard deviation of the participants' delivered force (F_i) normalised by the mean force ($\bar{F}$).[1,7] This parameter represents the precision index since it expresses the variability of force trace and it is independent of the target.

$$CV = \frac{\sqrt{\frac{\sum(F_i - \bar{F})^2}{n_i}}}{\bar{F}}$$

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 ($\frac{\sum MD_i}{4}$) and of CV $\left(\frac{\sum CV_i}{4}\right)$ 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, removing first second (Right Hand: $r\text{MD}_{1\text{-}12}$, $r\text{CV}_{1\text{-}12}$, Left Hand: $l\text{MD}_{1\text{-}12}$, $l\text{CV}_{1\text{-}12}$). The mean of MD and CV of 12 epochs were calculated and the mean of the variables ($\overline{\text{MD}}$ and $\overline{\text{CV}}$) of R and L was collected.

$$\overline{\text{MD}} = \frac{(\frac{\sum rMD_i}{12}) + (\frac{\sum lMD_i}{12})}{2}$$

$$\overline{\text{CV}} = \frac{(\frac{\sum rCV_i}{12}) + (\frac{\sum lCV_i}{12})}{2}$$

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.

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

Secondary Variables

The secondary variables evaluated at baseline were sex (W/M), age (years), weight (Kg), height (cm), body mass index (BMI), hand dominance (right/left) and dexterity. 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.[33] Manual dexterity was assessed through the Rolyan® 9 Hole Peg Test (9HPT) in both hands according to Mathiowetz (1985).[34]

Study Size

Based on One-way ANOVA test, a sample of 300 participants was determined to accept a power of 95%, a significant level of 0.05 and an effect size of 0.25.[35]

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 analised with non-parametric tests.

Descriptive statistics were carried out to understand the sample's characteristics. Values that exceed ±3 standard deviations were considered outliers and excluded from the analysis.

Kruskal-Wallis test was conducted to compare variables' main ranks among women and men age groups. Significant results were followed up using pairwise Mann-Whitney U-Tests. The significance acceptance level for pairwise comparison has been adjusted for the number of comparisons (k=10) using the Bonferroni Correction. 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 significant comparison in all tasks and was interpreted: ≤0.059 (small effect), 0.06- 0.139 (moderate effect), and ≥0.14 (large effect).[36]

Mann-Whitney U-test was used to compare primary variables medians in man/woman samples and dominant/non-dominant hand. The main effects of the comparison were reported as eta-squared (η^2).

Spearman's correlation analysis was performed to investigate the correlations between the different variables and the anthropometric characteristics of the sample such as the dexterity. The correlation strength was defined as very-high ($\rho > 0.9$), high ($\rho = 0.7$–0.89), moderate ($\rho = 0.5$–0.69), low ($\rho = 0.3$–0.49), or very low ($\rho < 0.29$).[37]

Results

Sample characteristics

Three hundred and thirty-six people were recruited in the study, 8 participants were excluded because identified as outliers. The final sample size was made by 328 participants (169 women and 159 men). Sample characteristics were summarized in Table 2.

Main findings

Sustained Contraction

The time parameter in SC test appears to be stable through the different age subgroups in men in both hands (Table 3 and Graph 1), confirmed by Kruskal-Wallis H tests (Table 4), in which no significant main effects were found.

Instead, women +75y and 60-74y subgroups showed higher medians in both dominant (DH) and non-dominant hand (NDH) (Table 3), respectively. Kruskal-Wallis H tests confirmed significant differences between medians of age subgroups in both hands, with small effect sizes (Table 4). Time parameter did not show difference between hands either in whole sample nor in each age subgroup (p>.05 in Mann-Whitney U-tests). Lastly, significant but small lower duration in SC of men compared to women emerged by Mann-Whitney U-test in both hands (p<.05) (Table 5).

Dynamic Contraction

Medians of MD, CV of DC test, in both hands, raise according to the increasing of participants' age (Table 3 and Graphs 2,3), difference between age-groups medians was significant in both sexes and hands with almost all large effect sizes. In particular, medians of MD and CV of 18-29y and 30-44y age groups were significantly lower compared to ones of +75y subgroups in both hands and sexes (Table 4).

Difference between sexes was observed: Mann-Whitney U-tests revealed higher medians of women especially in MD (medium effect size) but also in CV (small effect size) in both hands ($p<.001$) (Table 5).

Mann-Whitney U-tests between dominant and non-dominant hands showed no significant difference ($p>.05$).

Bimanual Strength Coordination

Similar findings were found in MD, CV, TTR of BSC test, which follow the same aforementioned relationships with age (Table 3 and Graphs 4,5,6) of DC. Kruskal-Wallis H tests showed statistically significant large difference between age groups, as resulted in the post-hoc tests +75y which exhibited worst medians in all parameters, with large effect size compared to 18-29y, 30-44y, 45-59y subgroups in both sexes (Table 4).

Significant different medians of MD, CV and TTR resulted between sexes, showing better parameters in men compared to women, with medium effect size for MD and CD and small one for TTR (Table 5).

Correlations

Spearman's rank correlations between parameters, pulp pinch MVCs and secondary variables were reported in Table 6.

Time parameters of DH and NDH hands were *moderately correlated*, instead time did not correlate with parameters of DC and BSC (Table 6).

Moderate correlations between hands were observed in MD and CV of DC test and in the same hand between MD and CV (Table 6).

In BSC *moderate to high* correlations emerged between variables (Table 6).

MVCs correlated *very poorly* to *poorly* and negatively with all primary variables (i.e., Time of SC test, MD and CV of DC test, MD, CV and TTR of BSC test) (Table 6).

Discussion

In this cross-sectional study, unlike all other parameters, time was the only one that did not worsen with age. Results were consistent with previous sEMG studies which observed lower muscle fatigability in the elderly.[38] The reasons could be attributed to difference in type I and II fibers proportion and in motor units firing rate that differentiate young from older people.[39,40]

At present, no previous studies had indagated normative data of endurance of pinch contraction, so that, it is not possible to compare our results with other data. The majority of endurance tasks, proposed in the literature for the assessment of other body regions, are based on body-weight resistance and their results differed from our findings.[10,41,42] In Sorensen test,[10] a higher endurance was found in the woman sample compared to the man one, but, relationship with age was negative in both sexes. Instead, in half squat, bilateral straight-leg raise endurance tasks[41] and deep neck flexors endurance[42] men performed better.

Studies analysing upper limb suggested controversial results about sex difference in the endurance tests during handgrip contractions, no difference [43–45] or the women's fatigability lower than the men's [46,47] were reported.

However, they agree with our findings that MVC and time are negatively correlated,[48] so that sex differences may be depended partially by lower maximal strength in women compared to men, but it cannot be exhaustive since the correlation between time and MVC in our study is low. The difference in fatigability may depend also on the variation of muscle length and muscle mass. De Haan et al. suggested that, between muscles of similar cross-sectional area, the longer ones have higher metabolic cost since they have more sarcomeres in series. For that reason, they showed a lower endurance capacity.[49] Moreover, during a muscle contraction, the greater the muscle mass the higher the intramuscular pressure, which is directly proportional to blood flow restriction. Finally, the reduced blood flow decreases the delivery of glucose, oxygen and catabolites, causing higher fatigability.[50,51]

Regarding the DC test, both accuracy and precision, measured by MD and CV respectively, decreased with the increase of people's age in both hands, according to previous findings in similar tasks.[7,52] The curvilinear relationships through the different age-groups (Graphs 2 and 3) could be explained by the physiological changes in the neuromusculoskeletal apparatus due to aging i.e., spinal motoneurons loss,[53,54] peripheral denervation,[55] increase in motor units size caused by reinnervation of collateral sprouting,[56] reduction in the neuromuscular junction of synaptic vesicles and of post-synaptic receptors, [57,58] loss in tactile sensitivity.[59]

However, it seems that elderly people, whose hobbies required high manipulative skills, have performance comparable to younger adults.[13] This finding may explain the larger scores variability observed in 60-74y and +75y subgroups. Hence, it is important to investigate accuracy and precision during a motor control assessment, because these parameters can be improved through focused training, even in old age people.[60,61]

MD and CV were found significantly higher in women than men. In other studies which proposed pinch precision tasks, the results were heterogeneous and conflicting.[7,62] The accuracy data retrieved by Herring-Marler et al. [7] seems to oppose to ours since women resulted more accurate than men. This mismatch could be due to the different nature of the studies since their participants had to perform 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 parameter 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 (*very low* correlation with MVC; r=.293, p<.01),[62] on the contrary MD is a relative index having as its denominator the target force. Since the target force is influenced by participants' MVC, while the MVC increases, the MD decreases. This could explain the higher correlation of MD with MCV

(Table 6) compared to RMSE. Since women showed lower strength than men, we hypothesised that these conflicting results between sexes may depend on the difference between the two aforementioned parameters (i.e., RMSE and MD). This hypothesis is also supported by the results of Shim et al.,[62] in which in their ramp force production test RMSE was lower in women, but, after normalisation by the MVC, men were more accurate than women both in young and elderly samples. We preferred MD to RMSE since we had to define the average of several epochs set on different force-levels so that a relative index was necessary.

According to De Serres and Fang findings,[19] no significant difference in variability was observed between DH and NDH hands. So that, hand dominance seems not to influence precision and accuracy of exerted force during a force-matching task guided by visual feedback.

With BSC we would investigate the ability to synchronize force between hands. This test requires organisation not only at the peripheral neuromuscular level but involves also interhemispheric crosstalk.[63] Results showed that MD, CV and TTR followed a curvilinear positive relationship with participants' age, corroborating the interlimb coordination decline in elderly both in terms of force and dexterity.[16,64–68] Our findings were in line with the anatomic and functional changes in central nervous system due to ageing. Compared to young adults, older people showed neural over-recruitment in bimanual coordination [69] and a greater loss in white matter that involves the corpus callosum.[70] This important part of the brain is implied in interhemispheric facilitatory and inhibitory interactions, which set the basis for and could affect bimanual coordination.[71,72] Differences in the corpus callosum size were observed also between sexes,[73] which could explain in part our findings, in all parameters of BSC task, men outperformed women, according with previous results in bimanual coordination tasks guided by visual feedback.[74,75]

BSC showed overall MD and CV scores over twice in both dominant and non-dominant hand compared to DC in every age group (table 3). Those findings could be due to the higher number of targets in BSC that produces more cognitive and physical fatigue and induces a loss in precision and accuracy.[1] However, this discrepancy between tests was probably due to the higher cognitive demand of BSC, into which a combination of motor overflow and of bilateral deficit occur.[76–78]

Anyhow, the involvement of motor overflow and the bilateral deficit remains speculative and should be addressed in future studies.

In our population, in a visual feedback-based bimanual task, precision and accuracy of force and time to reach target were moderately to highly correlated with each other. It may be worth considering in future studies if such correlations are present in different clinical populations.

Lastly, even if 9HPT correlated with DC and BSC parameters, the relationship is low. Those findings suggested that dexterity tests are not exhaustive substitutes for the force control parameters investigated in the present study.

Conclusions

Pinch prehension is involved in many daily tasks such as writing, opening/closing a zip, and bimanual activities as tying the shoes.[79] These activities do not require maximal contraction, but submaximal forces exerted for short to long time. Hence, we hypothesized that SC, DC and BSC tests describe pinch function better than MVC.

SC, DC and BSC appeared to be valid tests to assess different domains of pinch force control. The normative data, reported in the present study, could represent a useful reference to provide with a more detailed assessment that goes beyond the MVC, assisting the clinical reasoning for a more appropriate therapeutic choice.

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Fig 1. System of measurement: digital pinch meters and strain gauge amplifier

Fig 2. Setting of experimental session. a) pinch gauge; b) strain gauge amplifier

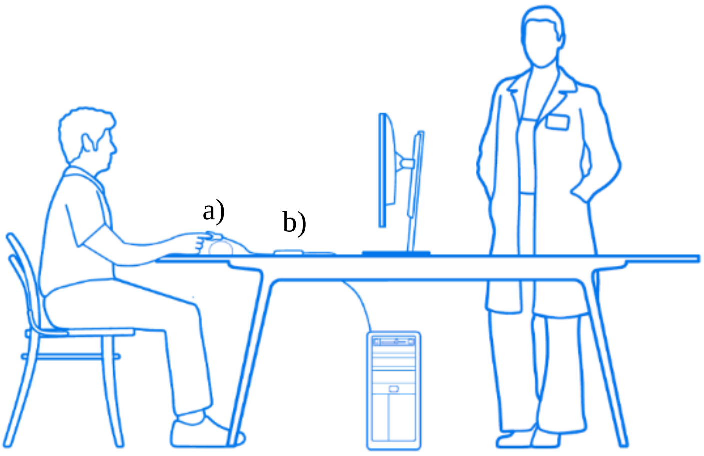


Fig 3. MVC Graphical User Interface

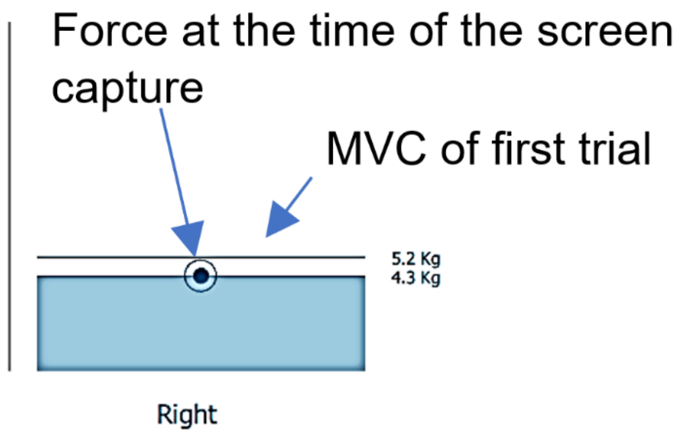


Fig 4. Sustained Contraction Graphical User Interface

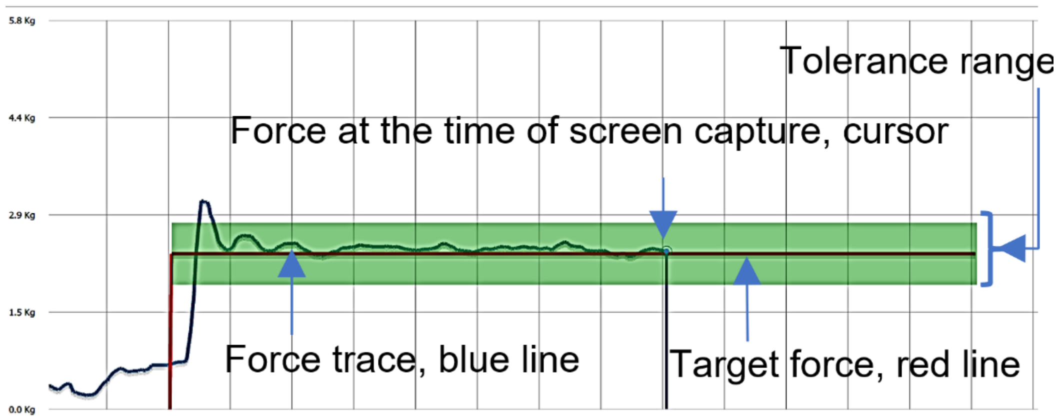


Fig 5. Dynamic Contraction Graphical User Interface. a) GUI during task; b) complete task view

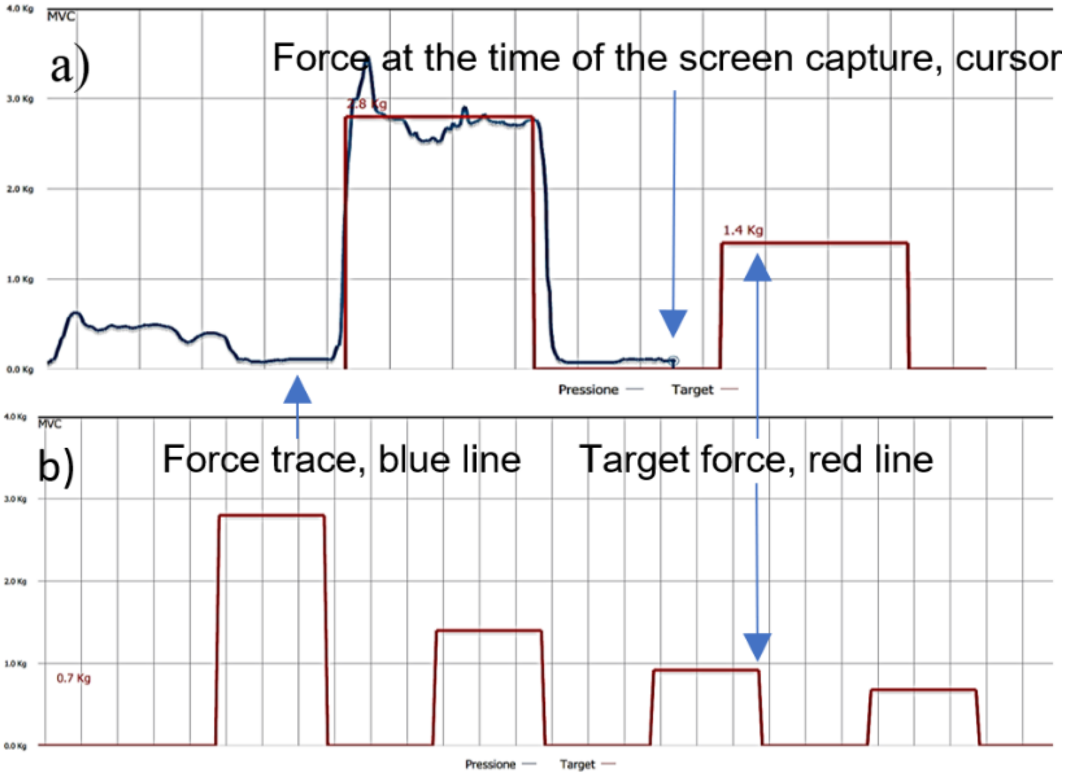


Fig 6. Bimanual Strength Coordination Graphical User Interface; a) Range of Force Polygon view and 12 targets; b) GUI during left, right, bilateral MVCs; c) GUI during task, detail of 70/70 %MVCs target. Note: L, Left; R, Right; MVC, Maximal Voluntary Contraction.

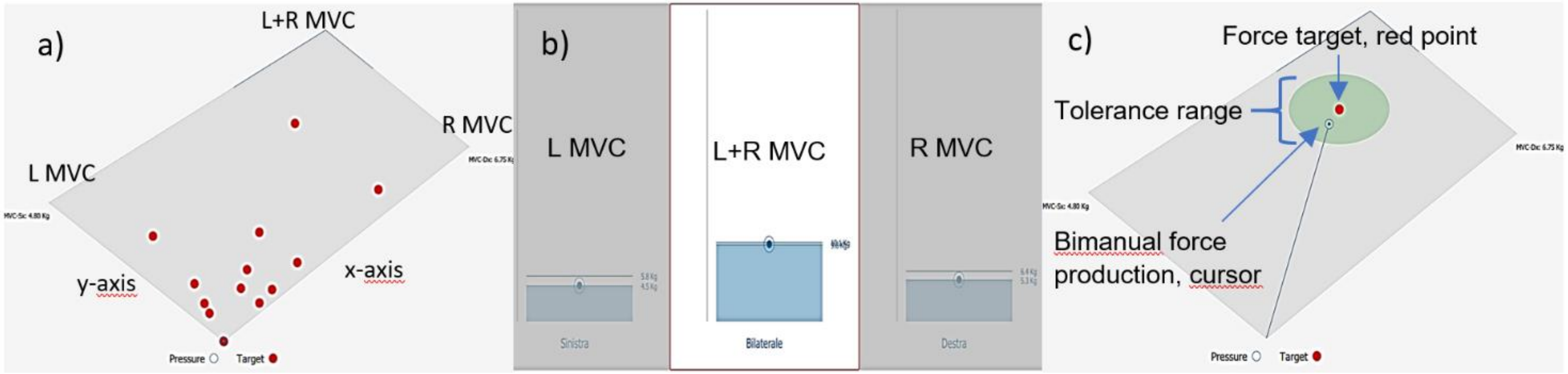


Table 1. Primary Variables of the study

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

Table 2. Descriptive analysis of participants

MEAN ± SD

age groups	**S**	**N**	**Age**	**RH:LH**	**Height (m)**	**Weight (kg)**	**BMI**	**MVC**		**9HPT**	
								DH (kg)	**NDH (kg)**	**DH (s)**	**NDH (s)**
18-29y	♀	33	24.5±3.05	29:4	1.66±0.06	60.3±12.8	21.6±3.40	3.75±0.80	3.41±0.81	17.3±2.17	18.9±2.12
	♂	35	25.0±2.84	32:3	1.77±0.05	72.4±7.36	23.0±1.92	5.39±1.11	4.73±0.93	18.3±1.78	19.6±1.76
30-44y	♀	35	36.7±4.97	32:3	1.64±0.05	60.1±10.0	22.2±3.07	3.93±0.94	3.60±0.84	17.4±1.73	18.8±1.96
	♂	32	35.7±4.44	28:4	1.79±0.06	81.7±13.4	25.2±3.61	5.74±1.13	5.51±1.21	18.2±2.29	19.9±3.05
45-59y	♀	35	53.3±4.29	33:2	1.63±0.06	65.1±13.0	24.2±4.28	3.72±0.84	3.17±0.77	18.2±2.60	19.9±2.34
	♂	32	52.3±4.20	25:7	1.77±0.05	79.9±11.0	25.3±2.75	5.62±1.42	4.96±1.33	18.8±2.33	20.9±2.96
60-74y	♀	34	66.0±4.41	31:3	1.60±0.04	69.2±13.7	26.9±5.48	3.31±0.72	2.83±0.57	20.7±3.98	21.8±3.77
	♂	31	65.5±3.98	28:3	1.75±0.07	85.4±12.4	27.6±3.16	5.34±1.14	4.77±1.03	22.1±3.45	22.9±2.84
75y+	♀	32	79.2±3.60	32:0	1.60±0.05	66.9±10.9	25.8±3.45	3.32±1.18	2.81±0.94	24.6±5.11	26.6±5.61
	♂	29	79.0±4.15	29:0	1.72±0.06	79.4±12.4	26.5±3.15	4.80±1.12	4.31±0.79	25.9±5.28	26.9±4.66
total	♀	169	51.7±19.8	157:12	1.63±0.06	64.3±12.7	24.1±4.50	3.61±0.93	3.17±0.85	19.6±4.29	21.1±4.45
	♂	159	50.4±19.8	142:17	1.76±0.06	79.6±12.2	25.4±3.34	5.39±1.22	4.86±1.13	20.5±4.33	21.9±4.10

Note: M, mean; SD, standard deviation; S, sex; N, number of people (outliers were excluded); 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; ♀, Women; ♂, Men

Table 3. Normative values of parameters of Sustained Contraction, Dynamic Contraction, Bimanual Strength Coordination

Part 1

		DH						**NDH**					
		SC		**DC**				**SC**		**DC**			
		TIME (s)		**MD**		**CV**		**TIME (s)**		**MD**		**CV**	
age groups	**sex**	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29y	♀	94,6	79,7 - 155,1	0,06	0,04 - 0,08	0,05	0,04 - 0,06	114,5	65,7 - 156,3	0,06	0,05 - 0,08	0,05	0,04 - 0,06
	♂	107,3	80,0 - 125,9	0,05	0,04 - 0,08	0,04	0,03 - 0,06	117,8	80,6 - 137,9	0,05	0,04 - 0,06	0,04	0,04 - 0,05
30-44y	♀	117,9	81,6 - 148,4	0,07	0,06 - 0,11	0,06	0,04 - 0,08	97,1	68,0 - 133,9	0,07	0,05 - 0,08	0,05	0,04 - 0,07
	♂	105,5	78,8 - 119,2	0,05	0,04 - 0,07	0,05	0,04 - 0,06	89,0	60,1 - 128,8	0,05	0,04 - 0,07	0,05	0,04 - 0,06
45-59y	♀	130,9	98,7 - 159,1	0,09	0,07 - 0,12	0,06	0,04 - 0,08	137,7	85,9 - 171,8	0,08	0,07 - 0,11	0,06	0,05 - 0,09
	♂	118,4	96,5 - 155,3	0,06	0,04 - 0,08	0,04	0,03 - 0,06	111,1	79,4 - 146,0	0,07	0,06 - 0,10	0,06	0,04 - 0,07
60-74y	♀	146,9	110,3 - 200,4	0,11	0,07 - 0,18	0,06	0,04 - 0,11	160,4	96,2 - 181,0	0,11	0,08 - 0,16	0,08	0,06 - 0,12
	♂	109,2	77,7 - 134,4	0,08	0,06 - 0,10	0,05	0,04 - 0,08	109,3	72,3 - 158,2	0,07	0,05 - 0,11	0,06	0,04 - 0,08
75y+	♀	148,7	99,1 - 180,5	0,14	0,09 - 0,20	0,11	0,06 - 0,16	113,5	72,4 - 193,6	0,14	0,10 - 0,21	0,10	0,08 - 0,13
	♂	115,8	68,7 - 157,5	0,10	0,07 - 0,13	0,07	0,05 - 0,09	107,5	71,5 - 132,7	0,11	0,07 - 0,11	0,07	0,06 - 0,11
total	♀	129,5	88,4 - 170,8	0,09	0,06 - 0,13	0,06	0,04 - 0,09	117,9	79,7 - 172,4	0,08	0,06 - 0,13	0,07	0,05 - 0,09
	♂	110,8	80,0 - 139,4	0,07	0,05 - 0,09	0,05	0,04 - 0,07	108,1	70,7 - 139,8	0,06	0,05 - 0,09	0,05	0,04 - 0,07

Part 2		**BSC**					
		MD		**CV**		**TTR (ms)**	
age groups	**sex**	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29y	♀	0,16	0,15 - 0,19	0,15	0,13 - 0,21	1164	974 - 1296
	♂	0,14	0,11 - 0,16	0,14	0,11 - 0,18	1106	984 - 1261
30-44y	♀	0,17	0,14 - 0,20	0,17	0,13 - 0,21	1165	950 - 140
	♂	0,15	0,12 - 0,17	0,14	0,11 - 0,17	1064	968 - 1217
45-59y	♀	0,21	0,15 - 0,25	0,21	0,15 - 0,27	1272	1110 - 1485
	♂	0,14	0,11 - 0,18	0,14	0,10 - 0,18	1025	852 - 1211
60-74y	♀	0,29	0,19 - 0,38	0,24	0,17 - 0,33	1416	1264 - 1588
	♂	0,17	0,15 - 0,21	0,17	0,14 - 0,23	1178	1047 - 1270
75y+	♀	0,33	0,30 - 0,44	0,32	0,24 - 0,36	1529	1282 - 1820
	♂	0,28	0,22 - 0,34	0,26	0,19 - 0,37	1434	1226 - 1711
total	♀	0,20	0,15 - 0,31	0,21	0,15 - 0,29	1286	1090 - 1506
	♂	0,16	0,12 - 0,20	0,16	0,12 - 0,21	1155	996 - 1338

Note: 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; ♀, Women; ♂, Men.

Table 4. Kruskal Wallis H test and Mann-Whitney post-hoc test with Bonferroni Correction

Part 1

							Mean Rank				
SEX	TASK	PRIMARY OUTCOME	hand	X^2	df	η^2	18-29y	30-44y	45-59y	60-74y	+75y
♀	SC	time	DH	**11,658**	4	**0,047***	69,70	71,56	86,74	102,78	94,69
			NDH	**11,787**	4	**0,047***	76,67	65,73	95,03	101,60	86,06
	DC	MD	DH	**48,166**	4	**0,269*****	46,32	70,43	83,64	102,93	123,27
			NDH	**56,668**	4	**0,333*****	46,62	60,81	87,29	109,50	122,50
		CV	DH	**33,431**	4	**0,179*****	59,44	75,80	75,71	91,76	124,39
			NDH	**47,226**	4	**0,264*****	54,65	63,17	80,99	102,44	126,03
	BSC	MD	BIL	**73,820**	4	**0,426*****	49,76	52,83	80,33	111,96	133,00
		CV	BIL	**43,333**	4	**0,24*****	57,23	62,16	82,03	101,03	124,84
		TTR	BIL	**32,754**	4	**0,175*****	60,11	64,97	80,94	105,79	114,92
♂	SC	time	DH	5,197	4	0,007	74,34	70,84	94,97	79,39	81,07
			NDH	4,932	4	0,006	84,89	66,09	84,63	88,32	75,45
	DC	MD	DH	**31,086**	4	**0,165*****	61,83	58,88	75,88	96,26	112,41
			NDH	**40,407**	4	**0,222*****	49,36	62,31	89,13	90,95	114,72
		CV	DH	**18,447**	4	**0,088****	68,51	72,84	65,11	90,34	107,14
			NDH	**29,139**	4	**0,153*****	54,91	65,78	81,11	94,05	109,72
	BSC	MD	BIL	**55,358**	4	**0,313*****	57,34	62,75	62,81	93,87	130,52
		CV	BIL	**49,175**	4	**0,275*****	59,79	64,52	61,55	93,39	127,53
		TTR	BIL	**32,119**	4	**0,171*****	74,09	65,19	60,72	84,03	120,45

Part 2

Mann-Whitney post-hoc tests (η^2)

SEX	TASK	PRIMARY OUTCOME	hand	18-29y vs 30-44y	18-29y vs 45-59y	18-29y vs 60-74y	18-29y vs +75y	30-44y vs 45-59y	30-44y vs 60-74y	30-44y vs +75y	45-59y vs 60-74y	45-59y vs +75y	60-74y vs +75y
♀	SC	time	DH	0,00	0,036	0,115	0,055	0,026	0,101	0,052	0,032	0,008	0,004
			NDH	0,01	0,036	0,065	0,006	0,104	**0,143***	0,033	0,006	0,005	0,017
	DC	MD	DH	0,09	**0,182****	**0,288*****	**0,508*****	0,028	0,11	**0,31*****	0,047	**0,214*****	0,037
			NDH	0,023	**0,221*****	**0,42*****	**0,48*****	0,094	**0,259*****	**0,335*****	0,067	**0,177****	0,037
		CV	DH	0,033	0,035	0,1	**0,404*****	0,00	0,026	**0,258*****	0,03	**0,259*****	0,107
			NDH	0,012	0,087	**0,213*****	**0,485*****	0,039	**0,158****	**0,419*****	0,054	**0,239*****	0,052
	BSC	MD	BIL	0,00	**0,133***	**0,436*****	**0,614*****	0,104	**0,358*****	**0,56*****	**0,127***	**0,36*****	0,076
		CV	BIL	0,002	0,075	**0,207****	**0,443*****	0,043	**0,159****	**0,38*****	0,036	**0,219*****	0,063
		TTR	BIL	0,002	0,054	**0,221*****	**0,287*****	0,035	**0,166****	**0,234*****	0,079	**0,132***	0,014
♂	SC	time	DH	np	np	np	np	np	np	np	np	np	np
			NDH	np	np	np	np	np	np	np	np	np	np
	DC	MD	DH	0,003	0,003	**0,159***	**0,297*****	0,031	**0,182****	**0,291*****	0,046	**0,146***	0,051
			NDH	0,034	**0,034****	**0,202****	**0,416*****	0,094	0,104	**0,345*****	0,00	0,094	0,073
		CV	DH	0,003	0,003	0,059	**0,162***	0,01	0,04	**0,144***	0,074	**0,19****	0,041
			NDH	0,016	0,016	**0,18****	**0,333*****	0,03	0,094	**0,227****	0,021	0,098	0,031
	BSC	MD	BIL	0,006	0,006	**0,197****	**0,562*****	0,00	**0,136***	**0,535*****	0,116	**0,453*****	**0,247*****
		CV	BIL	0,003	0,003	**0,154***	**0,5*****	0,003	0,115	**0,457*****	**0,132***	**0,428*****	**0,209****
		TTR	BIL	0,01	0,01	0,012	**0,272*****	0,005	0,051	**0,346*****	0,067	**0,35*****	**0,185****

Note: *, significant at 0.05; ** significant at 0.01; *** significant at 0.001; X2, Chi Square; df, degree of freedom; η^2, eta squared; ♀, Women; ♂, Men; 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.

Table 5. Mann-Whitney U Test of comparison between women and men samples.

			♀	♂	U	p-value	η2
SC	time	DH	129,49	110,78	10666,5	**0,001**	0,032
		NDH	117,91	108,05	11505,5	**0,025**	0,015
DC	MD	DH	0,09	0,07	9432,0	**0,000**	0,066
		NDH	0,08	0,06	8863,0	**0,000**	0,087
	CV	DH	0,06	0,05	10120,5	**0,000**	0,045
		NDH	0,07	0,05	9962,0	**0,000**	0.05
BSC	MD		0,2	0,16	8524,5	**0,000**	0,1
	CV		0,21	0,16	9389,5	**0,000**	0,068
	TTR		1286,3	1154,6	9779,0	**0,000**	0,055

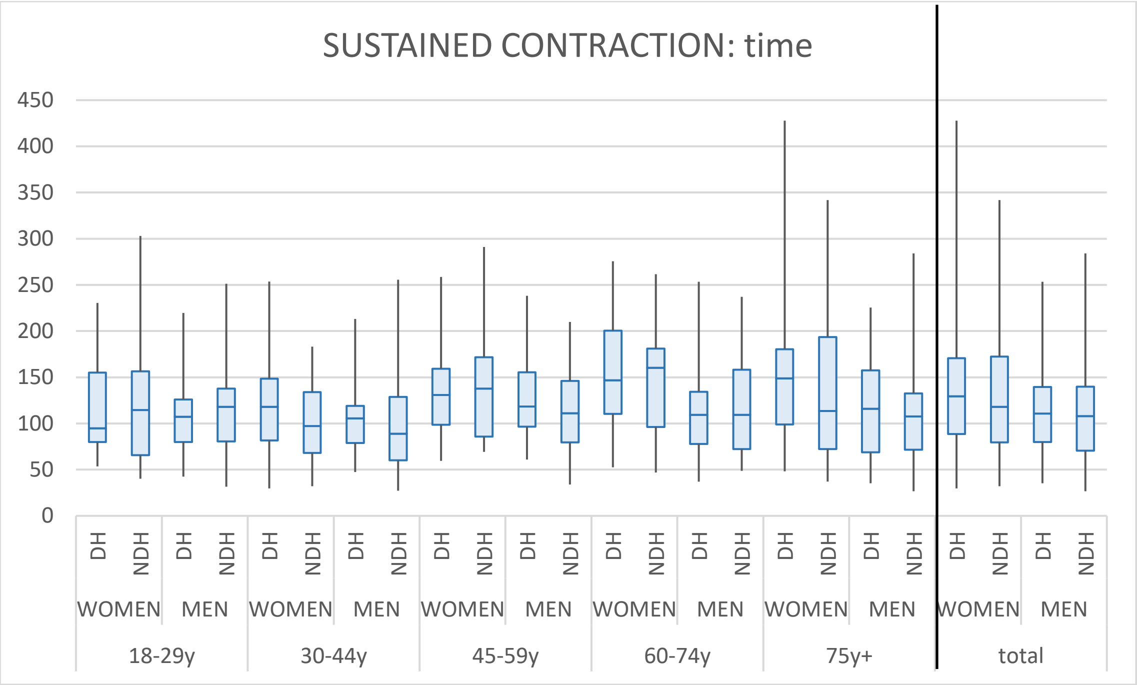
Note: ♀, Women; ♂, Men; η^2, eta squared; SC, Sustained Contraction; DC, Dynamic Contraction; BSC, Bimanual Strength Coordination; MD, Mean Distance; CV, Coefficient of Variability; TTR, Time To Reach; DH, Dominant Hand, NDH, Non-Dominant Hand.

Table 6. Spearman’s correlation analysis

Parameter		**DH**			**NDH**			**BSC**			**MVCs**		**Secondary Variables**					
		SC: Time	DC: MD	DC: CV	SC: Time	DC: MD	DC: CV	MD	CV	TTR	DH	NDH	Age	Height	Weight	BMI	DH 9HPT	NDH 9HPT
DH	SC:Time	1	0,097	**0,115***	**0,587****	0,080	0,097	**0,139***	**0,115***	0,099	**-0,255****	**-0,220****	**0,171****	**-0,147****	**-0,243****	-0,026	-0,024	0,001
	DC: MD		1	**0,597****	0,095	**0,653****	**0,456****	**0,598****	**0,467****	**0,315****	**-0,348****	**-0,371****	**0,478****	-0,090	**-0,360****	**0,147****	**0,337****	**0,330****
	DC: CV			1	**0,129***	**0,385****	**0,547****	**0,566****	**0,495****	**0,350****	**-0,291****	**-0,298****	**0,363****	-0,029	**-0,268****	**0,157****	**0,338****	**0,341****
NDH	SC:Time				1	0,094	**0,175****	0,076	0,048	0,049	**-0,201****	**-0,260****	0,101	-0,087	**-0,180****	-0,010	0,026	0,030
	DC: MD					1	**0,660****	**0,539****	**0,441****	**0,365****	**-0,319****	**-0,369****	**0,522****	-0,011	**-0,361****	**0,239****	**0,324****	**0,340****
	DC: CV						1	**0,527****	**0,458****	**0,353****	**-0,271****	**-0,342****	**0,475****	-0,028	**-0,329****	**0,195****	**0,353****	**0,405****
BSC	MD							1	**0,828****	**0,622****	**-0,361****	**-0,417****	**0,575****	-0,056	**-0,354****	**0,187****	**0,451****	**0,472****
	CV								1	**0,686****	**-0,344****	**-0,385****	**0,484****	-0,108	**-0,303****	0,078	**0,383****	**0,418****
	TTR									1	**-0,243****	**-0,271****	**0,374****	-0,081	**-0,252****	0,068	**0,310****	**0,311****

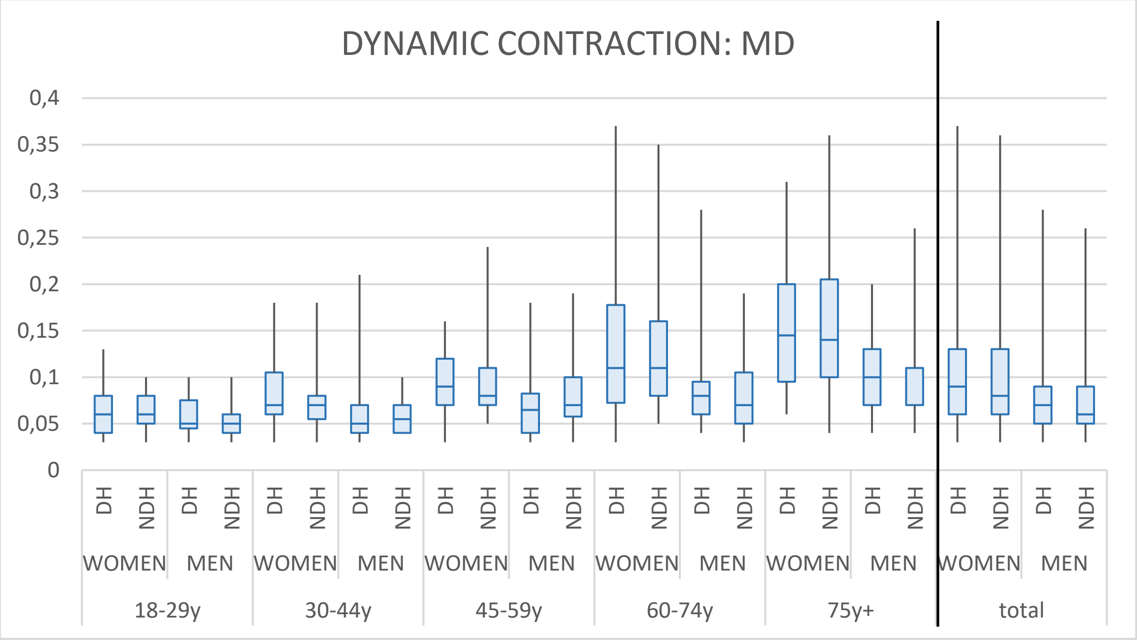
Note: **. Correlation is significant at the 0.01 level; *. Correlation is significant at the 0.05 level; SC, Sustained Contraction; DC, Dynamic Contraction; BSC, Bimanual Strength Coordination; MVCs, Maximal Voluntary Contractions; MD, Mean Distance; CV, Coefficient of Variability; TTR, Time To Reach; DH, Dominant Hand, NDH, Non-Dominant Hand; BMI, Body Mass Index; 9HPT, 9 Hole Peg Test

Graph 1. Time parameter in Sustained Contraction, boxplots show time over sexes and age groups



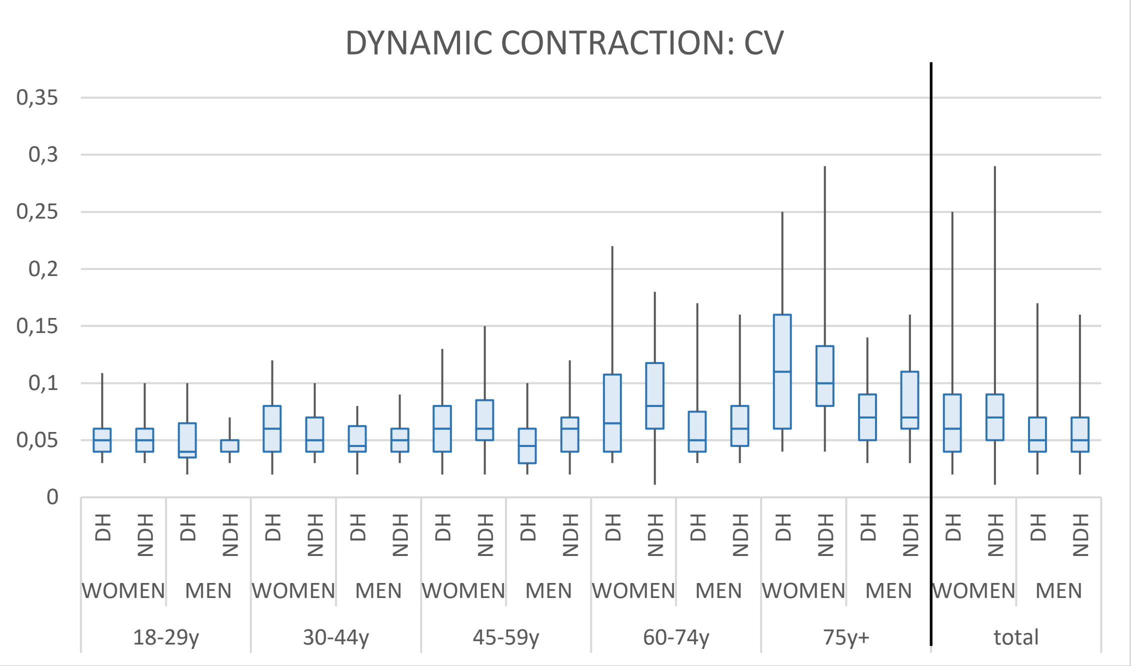
Note: DH, Dominant Hand; NDH, Non-Dominant Hand

Graph 2. Mean Distance parameter in Dynamic Contraction, boxplots show MD over sexes and age groups



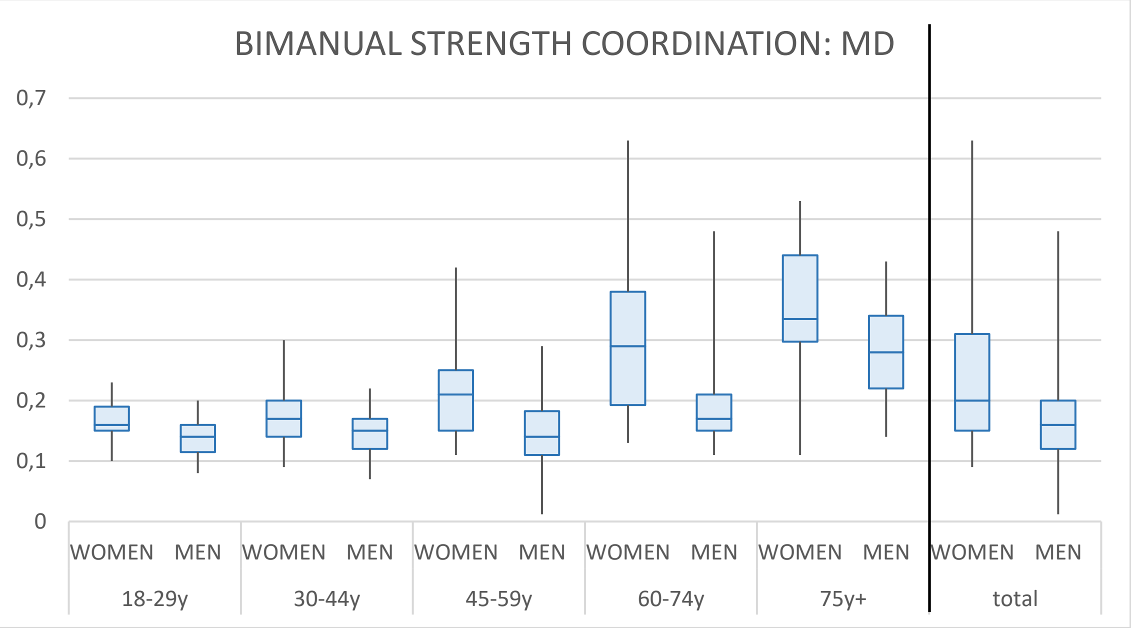
Note: DH, Dominant Hand; NDH, Non-Dominant Hand

Graph 3. Coefficient of Variability parameter in Dynamic Contraction, boxplots show CV over sexes and age groups



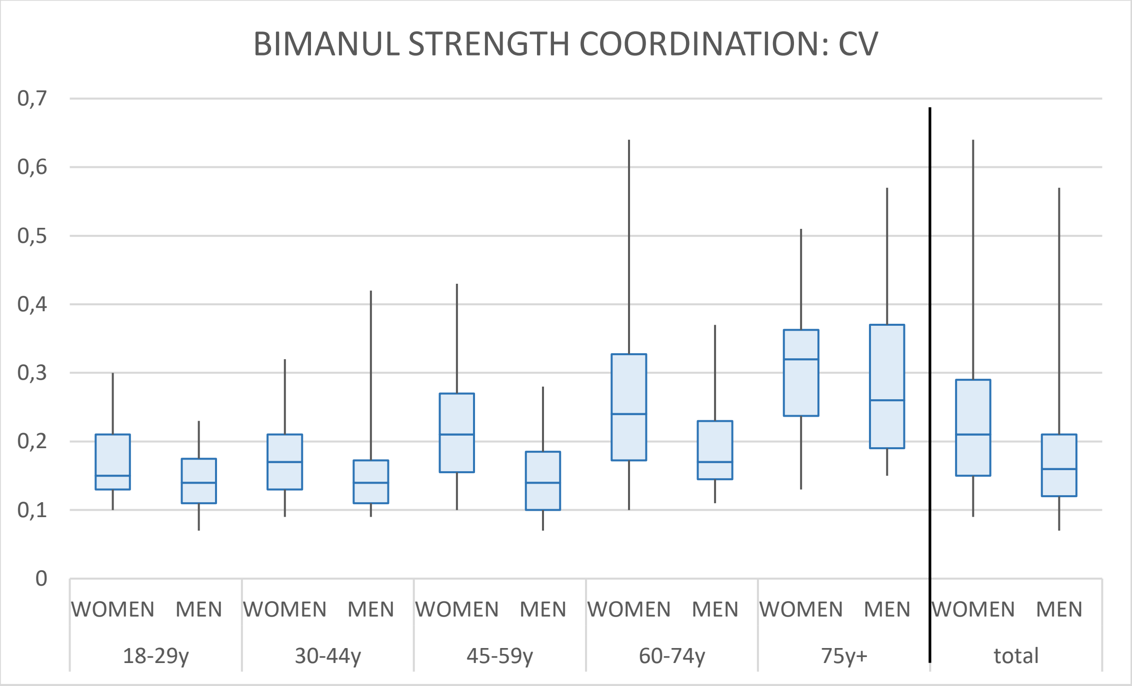
Note: CV, Coefficient of Variability; DH, Dominant Hand; NDH, Non-Dominant Hand

Graph 4. Mean Distance parameter in Bimanual Strength Coordination, boxplots show MD over sexes and age groups



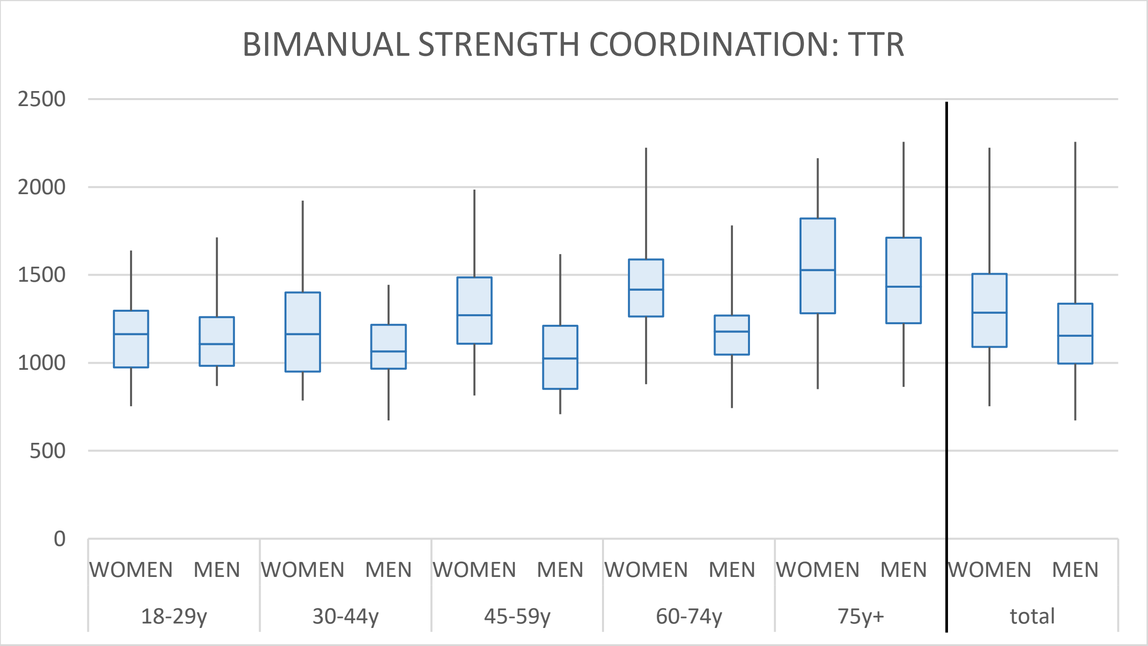
Note: MD, Mean Distance

Graph 5. Coefficient of Variability parameter in Bimanual Strength Coordination, boxplots show CV over sexes and age groups



Note: CV, Coefficient of Variability

Graph 6. Time-To-Reach parameter in Bimanual Strength Coordination, boxplots show TTR over sexes and age groups



Note: TTR, Time-To-Reach

GENERAL DISCUSSION

Every chapter of this dissertation contains a thorough discussion concerning the specific topic investigated. This last section analyses some critical points, emerged from the discussions of each chapter, offering some suggestions that may be helpful for future studies on pinch force control and implementation of the multiparametric pinch evaluation in clinical practice.

Clinical implications

In this Ph.D. project, a multiparametric evaluation of pinch force control measured through load cells was presented, which proved to be reliable and consistent. Before investigating the tasks in affected hands, in clinical settings it is important to identify the scores of the variables that could be considered as the reference. For this reason data of pinch force control were collected from Italian healthy sample and analysed. Table 1 summarises the main results that emerged from the Ph.D. project, showing the measures of central tendency of the variables, means or medians, and their respective measure of dispersion, standard deviation or quartile 1-3. Data were presented stratifying population per sex and per age groups (18-29y, 30-44y, 45-59y, 60-74y, +75y).

Quantifying specific impairments allows clinicians, especially physical therapists but also surgeons, to propose interventions that are more targeted to the patient’s needs. As suggested by Piacenza et al.,[1] for example people with thumb carpometacarpal osteoarthritis who undergo surgery may benefit more from arthroplasty rather than arthrodesis if their goals are more focused on force accuracy recovery than maximal strength.

The constructs investigated in this thesis were maximal strength, endurance, precision and accuracy of force, and lastly bimanual coordination, through their respective tasks: MVCs in Tip, Palmar pinch and thumb-index Extension, Sustained Contraction, Dynamic Contraction, Bimanual Strength Coordination.

Pinch MVC is certainly an important parameter to assess hand impairments,[2–5] as well as being a possible substitute for the handgrip strength to detect people with general muscle weakness.[6–8] Moreover it is widely used in the clinical setting since it is easy and quick to familiarize with and to perform. However, pinch MVC showed a low correlation with parameters of SC, DC, and BSC (chapter 4). As consequence, maximal strength is not sufficient to detect differences in hand motor control between individuals[9,10] and so the therapeutic proposal based only on strength evaluation may not meet the needs of the patient, highlighting the importance of a multiparametric evaluation.

Another major aspect of clinical interest that emerged in this project was the progressive decline not only of pinch strength but also of accuracy and precision of force in unimanual activities and bimanual coordination in elderly people. The loss of hand motor control may produce a large variety of obstacles in daily activities. However, the decline was not present in all the elderly, some participants showed similar scores even to young adults. To detect who shows low strength, endurance or within- and between-hand force coordination could aim at increasing quality of life in the frail population since targeted rehabilitation programmes could be proposed.[11]

Future directions

In every task, various prospects in the research field emerged from this Ph.D. project, and they are briefly discussed below.

Pinch MVC revealed two major findings, the importance to investigate in terms of workload level the patient's occupation, and the strength loss across the lifespan.

First, the results showed no strength-difference between hands in people employed in heavy physical occupations. Likely, the strength is based more on the frequency and demand of the hand rather than the mere hand dominance. As consequence, the occupation should be considered during assessment in people with hand injury, because, in order to return to work, people employed in heavier jobs need not only higher hand strength but also to regain a balanced strength between limbs.

Second, the exponential age-related decline in pinch strength is consistent with the progress of muscle loss. Considered the practicality of the test, further studies should investigate if pinch strength could be used to detect sarcopenia in general population.

Thumb-index extension MVC (E-MVC) is not a functional task, however, it involves muscles that are important for the dynamic stabilisation of the thumb carpometacarpal joint,[12] and a severe deficit of those muscles leads to an inability to open hand and as consequence to grasp.[13] It deserves to be investigated in thumb carpometacarpal osteoarthritis to guide muscle strengthening,[12,14] carpal tunnel syndrome to investigate the severity[15] and after stroke since deficits in extension muscles seem to be related to low grasp performance.[13]

The Sustained Contraction task resembles the real functional demands of the hand. Many daily activities required sustained contractions of thumb and index, such as in handwriting, using tweezers, holding a smartphone. Moreover, in many professional activities, static grips are needed, like embroidering or holding a mouse. Also in physical therapy, there are manual techniques in which prolonged stabilization of the thumb is necessary, such as trigger point pressure release or ischemic compression. Future research could confirm the hypothesis that pinch sustained contraction task could represent an important functional outcome of affected hands. Based on other body districts,[16,17] SC could be an interesting task in musculoskeletal hand disorders in which pain is the main symptom, and it could be used in all the conditions affected by both central and peripherical fatigue.[18,19]

DC and BSC evaluate within- and between-hand force coordination respectively, needful for manipulation of objects. The first could be proposed to investigate diseases in which, even with visual feedback, there are large force variability, deficits in planning force modulation and large latency of force initiation.[20–24] The second needs to be investigated in situations in which, in addition to abovementioned impairments, may be deficits in interhemispheric interactions caused by callosal[25] or hemispheric damages (in particular to primary motor cortex, parietal cortex, supplementary motor area)[26–28], such as in many central nervous system diseases: Parkinson’s syndrome, post-stroke, multiple sclerosis, unilateral cerebral palsy.[29–34]

Strength and limitations

The research project presented in this thesis represents a proposal of various constructs of tasks for overcoming the lack of force control assessment of the hands. This thesis has limited the analysis to the healthy population and clinical impacts need to be investigated in future studies to understand the ability of tasks to find impairments in pathological populations.

An aspect to underlie is that the present project focused on tasks guided by visual feedback, the visual information assists the tactile one, modifying the force variability.[35,36] It is important to emphasise this aspect, because problems of sensory afference, for example in carpal tunnel syndrome, may not be revelated by DC and BSC since sensory deficits are vicariate by vision.[37] In peripheral neuropathies, impairments could emerge, however, through static force-matching tasks in which visual feedback, after a first period to memorize the somatosensory information, is removed, and the somatosensory feedback is isolated. Probably, people affected by peripheral neuropathies would perform worst than healthy individuals.[37] However, the reliability of those tasks must be confirmed by further studies.

Conclusions

This Ph.D. project has aimed to propose reliable tasks to quantitatively evaluate pinch force control and to investigate the parameters among the healthy population.

Parameters measured showed heterogenous relationships with age, sex, and dominance. Time in Sustained Contraction was the only parameter that did not get worse at increasing age, MVCs, MD and CV of Dynamic Contraction, MD, CV, and TTR of Bimanual strength coordination showed a progressive decline across age groups. Differences between sexes emerged not only in MVC tasks, women showed higher endurance, on the contrary, pinch force control was more precise and accurate in men, in which better bimanual force coordination was also observed. Dominant hand differed from the contralateral only in pinch MVC tasks, no differences were found in E-MVC, and parameters of SC, DC, and BSC. Lastly, the correlations between parameters of different tasks were *very low* to *low*, confirming the difference in rationale between tests. The results become a starting point for future studies to define the specific impairments in force control of different neurological and musculoskeletal disorders. Moreover, once identified the impairments, research on the therapeutic proposal would represent an important area of interest to guide the rehabilitation process through specific exercises or the more fun and engaging exergames.

Table 1. Normative data stratified by age and sex, a summary of main results of PhD project.

Part1

		DH											
		MVC (kg)						SC		DC			
age groups		**TP-MVC**		**PP-MVC**		**E-MVC**		**TIME (s)**		**MD**		**CV**	
	sex	X̄	SD	X̄	SD	X̄	SD	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29y	♀	3,49	0,76	3,6	0,79	1,01	0,26	94,6	79,7-155,1	0,06	0,04-0,08	0,05	0,04-0,06
	♂	5,34	1,21	5,42	1,08	1,6	0,31	107,3	80,0-125,9	0,05	0,04-0,08	0,04	0,03-0,06
30-44y	♀	4,1	1	3,85	0,96	1,14	0,29	117,9	81,6-148,4	0,07	0,06-0,11	0,06	0,04-0,08
	♂	6,02	1,01	5,65	1,12	1,93	0,35	105,5	78,8-119,2	0,05	0,04-0,07	0,05	0,04-0,06
45-59y	♀	3,88	0,93	3,6	0,81	1,01	0,28	130,9	98,7-159,1	0,09	0,07-0,12	0,06	0,04-0,08
	♂	6,01	1,26	5,39	1,08	1,77	0,46	118,4	96,5-155,3	0,06	0,04-0,08	0,04	0,03-0,06
60-74y	♀	3,6	0,7	3,3	0,74	0,89	0,26	146,9	110,3-200,4	0,11	0,07-0,18	0,06	0,04-0,11
	♂	5,98	1,21	5,34	1,13	1,8	0,4	109,2	77,7-134,4	0,08	0,06-0,10	0,05	0,04-0,08
75y+	♀	3,36	1,18	3,26	1,24	0,78	0,28	148,7	99,1-180,5	0,14	0,09-0,20	0,11	0,06-0,16
	♂	5,27	1,19	4,76	1,12	1,43	0,34	115,8	68,7-157,5	0,10	0,07-0,13	0,07	0,05-0,09
total	♀	3,69	0,96	3,52	0,94	0,97	0,29	129,5	88,4-170,8	0,09	0,06-0,13	0,06	0,04-0,09
	♂	5,73	1,21	5,32	1,13	1,71	0,41	110,8	80,0-139,4	0,07	0,05-0,09	0,05	0,04-0,07

Part 2

		NDH											
		MVC (kg)						SC		DC			
age groups		**TP-MVC**		**PP-MVC**		**E-MVC**		**TIME (s)**		**MD**		**CV**	
	sex	X̄	SD	X̄	SD	X̄	SD	M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29y	♀	3,29	0,89	3,3	0,7	1,02	0,21	114,5	65,7-156,3	0,06	0,05-0,08	0,05	0,04-0,06
	♂	4,86	1,19	4,69	0,95	1,5	0,34	117,8	80,6-137,9	0,05	0,04-0,06	0,04	0,04-0,05
30-44y	♀	3,61	0,97	3,56	0,83	1,08	0,34	97,1	68,0-133,9	0,07	0,05-0,08	0,05	0,04-0,07
	♂	5,53	1,13	5,33	1,27	1,82	0,43	89,0	60,1-128,8	0,05	0,04-0,07	0,05	0,04-0,06
45-59y	♀	3,52	0,79	3,16	0,77	0,96	0,3	137,7	85,9-171,8	0,08	0,07-0,11	0,06	0,05-0,09
	♂	5,5	1,27	4,83	1,21	1,61	0,43	111,1	79,4-146,0	0,07	0,06-0,10	0,06	0,04-0,07
60-74y	♀	3,16	0,62	2,92	0,62	0,8	0,24	160,4	96,2-181,0	0,11	0,08-0,16	0,08	0,06-0,12
	♂	5,52	1,26	4,78	1,05	1,61	0,35	109,3	72,3-158,2	0,07	0,05-0,11	0,06	0,04-0,08
75y+	♀	2,99	1,09	2,76	0,98	0,75	0,27	113,5	72,4-193,6	0,14	0,10-0,21	0,10	0,08-0,13
	♂	4,64	1,07	4,26	0,82	1,34	0,44	107,5	71,5-132,7	0,11	0,07-0,11	0,07	0,06-0,11
total	♀	3,31	0,9	3,14	0,83	0,92	0,3	117,9	79,7-172,4	0,08	0,06-0,13	0,07	0,05-0,09
	♂	5,22	1,23	4,79	1,12	1,58	0,43	108,1	70,7-139,8	0,06	0,05-0,09	0,05	0,04-0,07

Part 3

age groups	sex	BSC					
		MD		CV		TTR (ms)	
		M	Q1-Q3	M	Q1-Q3	M	Q1-Q3
18-29y	♀	0,16	0,15 - 0,19	0,15	0,13 - 0,21	1164	974 - 1296
	♂	0,14	0,11 - 0,16	0,14	0,11 - 0,18	1106	984 - 1261
30-44y	♀	0,17	0,14 - 0,20	0,17	0,13 - 0,21	1165	950 - 140
	♂	0,15	0,12 - 0,17	0,14	0,11 - 0,17	1064	968 - 1217
45-59y	♀	0,21	0,15 - 0,25	0,21	0,15 - 0,27	1272	1110 - 1485
	♂	0,14	0,11 - 0,18	0,14	0,10 - 0,18	1025	852 - 1211
60-74y	♀	0,29	0,19 - 0,38	0,24	0,17 - 0,33	1416	1264 - 1588
	♂	0,17	0,15 - 0,21	0,17	0,14 - 0,23	1178	1047 - 1270
75y+	♀	0,33	0,30 - 0,44	0,32	0,24 - 0,36	1529	1282 - 1820
	♂	0,28	0,22 - 0,34	0,26	0,19 - 0,37	1434	1226 - 1711
total	♀	0,20	0,15 - 0,31	0,21	0,15 - 0,29	1286	1090 - 1506
	♂	0,16	0,12 - 0,20	0,16	0,12 - 0,21	1155	996 - 1338

Note: ♀, Women; ♂, Men; DH, Dominant hand; NDH, Non-dominant hand; MVC, Maximal voluntary contraction; SC, Sustained Contraction; DC, Dynamic Contraction; BSC, Bimanual Strength Coordination; MD, Mean Distance; CV, Coefficient of Variability; TTR, Time To Reach; TP, Tip Pinch; PP, Palmar Pinch; E, Extension; $\bar{X}$, Mean; SD, Standard deviation; M, median; Q1-Q3, Quartile 1-Quartile 3.

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