Musculoskeletal Science and Practice 55 (2021) 102432

Contents lists available at ScienceDirect

Musculoskeletal Science and Practice

journal homepage: www.elsevier.com/locate/msksp

Original article

Impairments in grip and pinch force accuracy and steadiness in people with osteoarthritis of the hand: A case-control comparison

Nicoló Edoardo Magni [a,*], Peter John McNair [a], David Andrew Rice [a,b]

[a] Health and Rehabilitation Research Institute, Auckland University of Technology, 90 Akoranga Drive, Northcote, Auckland, 0627, New Zealand
[b] Waitemata Pain Service, Department of Anaesthesiology and Perioperative Medicine, North Shore Hospital, Waitemata DHB, 124 Shakespeare Road, Takapuna, Westlake, Auckland, 0622, New Zealand

ARTICLE INFO

Keywords:
Symptomatic hand osteoarthritis
Force steadiness
Force matching
Root mean square
RMS
Hand function

ABSTRACT

Background: Symptomatic hand osteoarthritis (OA) is severely disabling condition. Limited evidence has focused on force control measures in this population.
Objectives: It was the aim of the present study to determine whether force matching accuracy and steadiness are impaired in people with hand OA. In addition, the relationship between force control measures (accuracy and steadiness) and measures of hand function and pain in people with symptomatic hand OA was explored.
Design: Case-control study.
Method: Sixty-two participants with symptomatic hand OA and 26 healthy pain-free controls undertook an isometric grip and pinch force matching task at 50 % of their maximum voluntary contraction. Average pain hand pain was recorded. In addition, the Disability of the Arm Shoulder and Hand Questionnaire (DASH), and the Functional Index of Hand Osteoarthritis were collected.
Results: Grip force-matching accuracy and steadiness were significantly impaired in the hand OA group compared to controls ($P < 0.05$). Pinch force-matching error was greater in people with hand OA ($P < 0.05$), however, pinch force steadiness was not different between groups. There was a learning effect in people with hand OA, with resolution of force matching impairments with task repetition. A small positive correlation was identified between grip force control and the DASH. No association was found between other measures of force control and self-reported measures of function or pain.
Conclusions: People with hand OA presented with greater impairments in measures of submaximal force control. These were correlated with self-reported hand function but not pain. Future studies may wish to examine whether objective measures of functional performance are related to force-matching error and steadiness.

1. Introduction

Osteoarthritis (OA) is a leading cause of disability globally (Breedveld, 2004). The hand is commonly affected, with 20 % of adults over 70 years old presenting with both symptoms and radiographic features of hand OA (Zhang et al., 2002). People with hand OA have been shown to experience deficits in muscle strength of hand and forearm muscles (Bagis et al., 2003). While impairments in grip and pinch strength have been widely documented, limited research has focused on force control. The fine control of submaximal force levels may be important for tasks performed with the hand such as manipulating small objects, carrying and lifting weights and utilising tools for arts, crafts, and work-related tasks (Smaby et al., 2004).

There is some evidence of altered force control and reduced dynamic stability in people with hand OA (de Oliveira et al., 2011; Nunes et al., 2012; Lawrence et al., 2014, 2015). Compared to healthy controls, de Oliveira et al. (2011) and Nunes et al. (2012) noted that people with hand OA were less efficient, generating greater forces for prolonged periods of time compared to healthy controls when performing the same task. Additionally, Nunes et al. (2012) reported that greater grip force and longer grip force latencies were associated with poorer performance on the Moberg Pickup Test, which is a hand dexterity test, and higher

Abbreviations: OA, Osteoarthritis; DASH, Disability of the arm, shoulder, and hand questionnaire; ACR, American college of rheumatology; DIP, distal interphalangeal; MCP, metacarpophalangeal; SF-BPI, Brief Pain Inventory Short Form; MVC, Maximum voluntarily contraction; FIHOA, Functional index of hand osteoarthritis; RMS, Root mean square; SD, Standard deviation; BMI, Body mass index; n, Number of participants; NRS, Numerical rating scale.

* Corresponding author.
E-mail addresses: nico.magni@aut.ac.nz, nico.magni@aut.ac.nz (N.E. Magni), peter.mcnair@aut.ac.nz (P.J. McNair), david.rice@aut.ac.nz (D.A. Rice).

https://doi.org/10.1016/j.msksp.2021.102432
Received 13 April 2021; Received in revised form 13 July 2021; Accepted 20 July 2021
Available online 22 July 2021

levels of disability on the Disability of the Arm Shoulder and Hand (DASH) Questionnaire. Furthermore, the dynamic stability of tip to tip pinch has also been shown to be impaired in people with 1st cmcj OA compared to healthy controls. In particular, the ability to stabilise small springs at very low loads (~300 g) was impaired in subjects with thumb OA compared to healthy controls (Lawrence et al., 2014). Interestingly, some brain areas involved in dynamic stability when pinching, which include the sensory, motor, and supplementary motor cortices (Mosier et al., 2011), have been previously suggested to be impaired in people with symptomatic hand OA (Magni et al., 2018). It is therefore possible that neuroplastic brain changes may, at least in part, be responsible for these impairments.

Nociception and/or acute joint pain may also impair muscle force control. Utilising an experimental model of knee pain, Rice et al. (2015) demonstrated that quadriceps force steadiness was impaired whilst participants were in pain and improved upon pain resolution. Only one study has assessed the relationship between pain and force control in subjects with hand OA. Nunes et al. (2012) noted a correlation between the Visual Analogue Scale and grip force at an object's lift off time. The deleterious effect of nociception on force control may be mediated by the activation of group III and IV afferents (Salahzadeh et al., 2013; Baker et al., 2002) potentially modulating activation of gamma motoneurons (Capra and Ro, 2000), which are responsible for attuning the discharge threshold of muscles spindles. Deviations from the normal resting state of muscle spindle may then indirectly impair neuromuscular control (Proske and Allen, 2019; Proske and Gandevia, 2012). It is also possible that ongoing nociceptive input may lead to neuroplastic changes within sensorimotor areas of the brain responsible for neuromuscular control. Considering that these cortical areas are highly involved in the control of force magnitude during pinching tasks (Holmström et al., 2011), it is plausible that functional alterations may affect submaximal force control. Of note, experimental hand pain has been shown to modify motor cortex excitability (Schabrun and Hodges, 2012) and the extent of motor cortex remodeling has been shown to correlate with impairments in force control in people with symptomatic knee OA (Shanahan et al., 2015).

Several measures of force control have been utilised in the literature. For the current study, the root mean square (RMS) error, the standard deviation (SD), and the coefficient of variation (CoV) of the force signal were adopted. The RMS provides a measure of force matching accuracy by taking into account the target force level by subtracting the target force from the force generated by the participants. In contrast, the SD of the force signal provides a measure of force steadiness without taking into account the target force. The CoV is another measured of force steadiness which quantifies the deviation of force traces from the signal average. Traditionally, RMS, SD, and CoV are calculated during submaximal force tasks. Considering that hand strength has been previously identified as a latent domain of hand function (Lawrence et al., 2015), it is possible that these measures of submaximal force control may be associated with self-reported hand disability. Thus, submaximal force control may be relevant in the execution of fine motor tasks such as the use of tweezers, forceps and screwdrivers (Smaby et al., 2004; Carment et al., 2018; Godde et al., 2018). In people with knee OA, force matching accuracy and force steadiness have been shown to be lower compared to healthy controls (Hortobagyi et al., 2004). Importantly, these measures are associated with functional performance deficits in stair climbing ability and balance (Hortobagyi et al., 2004). Furthermore, the magnitude of force control impairments is not related to muscle strength deficits (Laidlaw et al., 1999), suggesting that this is a specific motor impairment that deserves further investigation in people with hand OA.

Finally, force matching can be considered a novel motor task, with several studies demonstrating improved task performance over repeated trials (Hortobagyi et al., 2001; Parker et al., 2017). Compared to healthy controls, people with hand arthritis initially demonstrate large errors in finger twitch direction accuracy during a novel motor learning task (Parker et al., 2017). However, this error has been shown to reduce with practice, approaching that of the control group with repeated trials (Parker et al., 2017). It remains unknown whether impairments in force control are worse during initial trials or improve with practice in people with hand OA.

Considering the above points, the primary aim of this study was to examine whether force control measures are impaired in people with hand OA compared to healthy controls. Secondary aims were to explore whether force control measures are related to measures of hand function and pain and whether force control impairments improve with repeated trials in people with hand OA. Our main hypotheses were that: 1) people with hand OA would present with lower grip and pinch force-matching accuracy compared to healthy controls; 2) people with hand OA would present with lower grip and pinch force steadiness compared to healthy controls; 3) measures of grip and pinch force control would be related to self-reported measures of hand and upper limb function; 4) impairments in grip and pinch force control would be related to the average hand pain intensity in people with hand OA; 5) impairments in grip and pinch force control would be largest during the 1st trial in people with hand OA and 6) measures of grip and pinch force control would improve with repeated trials in people with hand OA and healthy controls.

2. Methods

2.1. Participants

Two groups of participants were recruited. The first group included 62 participants with symptomatic hand OA. Hand OA was confirmed through radiographic evidence and the American College of Rheumatology clinical criteria (Altman et al., 1990). The second group was composed of 26 age and gender matched participants without hand OA (data collected during 2019). The sample size of the hand OA group utilised for this study was much larger as baseline measures of grip and pinch force control were collected as part of an existing randomised controlled trial between 2017 and 2019 (Registration number: ACTRN12617001270303). See Table 1 for participants' eligibility criteria. Participants were excluded if they presented with or reported a

Table 1
Eligibility criteria, recruitment method and flow of participants' recruitment.

Study Information	Hand OA	Healthy pain-free controls
Eligibility criteria	Fulfils ACR criteria: Hand pain, aching, or stiffness and 3 or 4 of the following: - Hard tissue enlargement of 2 or more of 10 selected joints* - Hard tissue enlargement of 2 or more DIP joints - Fewer than 3 swollen MCP joints - Deformity of at least 1 of 10 selected joints* Radiographic evidence (Kellgren Lawrence > 1) No symptoms of upper limb radiculopathy No past or present Hx of neurological disease	Does not have: - Upper limb pain; - Cervical/Thoracic pain pathologies No signs or symptoms of upper limb neuropathy No past or present Hx of neurological disease
Source of participants	Hand therapy clinics & hand surgeons.	Staff recruited from the University and volunteers recruited from the community
Method of recruitment	Advertisement.	Snowball sampling

Note. ACR = American college rheumatology; DIP = distal interphalangeal; MCP = metacarpophalangeal; * = second and third distal interphalangeal (DIP), the second and third proximal interphalangeal, and the first carpometacarpal joints of both hands; Hx = History.

past history of neurological disease, an infection in the last three months, taking part in resistance training for the hands in the last six months, surgery to the hands in the last five years or joint injection in the last six months. Additional exclusion criteria were uncontrolled hypertension, a history of blood clot in the last 12 months, active cancer, a history of upper quadrant lymph node dissection, or rhabdomyolysis. All participants provided written informed consent for the experimental procedure. Ethical approval for the study was attained from the Health and Disability Ethics Committees (HDEC#: 16/CEN/191), in accordance with the principles set out in the declaration of Helsinki.

2.2. Sample size calculation

Using G*power 3.1.9.7 software (Faul et al., 2007) an a priori sample size calculation for an ANOVA within-between interaction was calculated. With an alpha level (p-value) of 0.05 and a power of 0.90, a correlation among repeated measures of 0.5 (between trial 1 and trial 5), a sample size of 23 in each group was required to detect a medium effect size (Cohen's f = 0.25). This effect size was selected based on previous research assessing forces at moment of object lift off (which is a submaximal force control measure) in people with hand OA compared to healthy control (de Oliveira et al., 2011).

2.3. Procedures

Demographic information (age, gender, height, weight) was collected from all participants. The number of painful joints (self reported number of painful joints other than the hand), and duration of pain (years) were assessed in those with hand OA pain only. Hand OA participants completed the Brief Pain Inventory Short Form (SF-BPI), which provided the average hand pain. This item was scored on an 11-points NRS scale with anchors of 0 = no pain and 10 = pain as bad as you can imagine. The SF-BPI has been validated against the visual analogue scale for pain showing a moderate to large correlation ($r > 0.6$) and it presents with good test-retest reliability ($r > 0.7$) (Mendoza et al., 2006). Participants with hand OA were asked to indicate preference in term of handedness. The most painful hand was tested. If both hands were equally painful, the dominant hand was tested. Control participants were recruited to ensure a similar age and gender balance to the hand OA group. The hand (dominant vs non-dominant) tested in controls was randomly selected using a computerised random number generator. All testing procedures took place in a single session of approximately 2 h. To minimise any effects of fatigue, rest periods were given between tests and all tests were performed in a random order. Data collection was performed in a laboratory setting utilising the same procedures and equipment. A research officer independent of the study authors completed all data collection.

2.4. Measures of hand function

Self-reported function was assessed in people with hand OA using the Disabilities of the Arm, Shoulder and Hand questionnaire (DASH) (0–100, with higher scores representing greater disability) (Beaton et al., 2001) and the Functional Index of Hand Osteoarthritis (FIHOA) (0–30, with greater scores representing greater disability) (Moe et al., 2010). These questionnaires were completed at the beginning of the experiment. The DASH has been validated against the SPADI and the Brigham function score with adequate correlations ($r > 0.7$), and its test re-test reliability is excellent (ICC: 0.96). The FIHOA has been validated against the AUSCAN showing a moderate correlation ($r = 0.76$), and its test re-test reliability is excellent (ICC: 0.94) (Moe et al., 2010).

2.5. Maximum voluntary contractions

Participants were seated in an adjustable chair with feet flat on the floor, back support, elbow in 90° of flexion, and wrist in 30° of extension (Trampisch et al., 2012; Villafañe and Valdes, 2014) (see Fig. 1). Grip and pinch strength were assessed through a digital hand and pinchmeter dynamometer (Biometric Ltd, Newport, UK). The digital hand dynamometer has been validated against a Jamar dynamometer and has shown good validity (ICC: 0.98) and test retest reliability (ICC: 0.99) (Allen and Barnett, 2011). The dynamometers were connected to a data acquisition board and the signal was transmitted to a customised computer software produced in LabVIEW (LabVIEW software, Version: 2013, Austin, TX, USA), which displayed strength data in real time. The hand dynamometer was kept in the second handle position for all participants (Trampisch et al., 2012). This position was found to be most comfortable for participants, and no patients had unusually large or small hands. The pinchmeter was held between the index and thumb (tip to tip pinch) (Villafañe and Valdes, 2014). To allow submaximal force matching targets to be individualised, grip and pinch strength testing was undertaken, with the highest force achieved in any of three trials recorded as the maximum voluntary contraction (MVC) (Gerodimos et al., 2017). Between the MVC and force matching tasks, we provided participants with a 5 min rest. A rest period of 30 s was given between each trial and participants were asked to hold the contraction for 7 s.

2.6. Force-matching task

Participants were seated as already described. The upper limb position for the force matching task was the same as that for the MVC testing. For both the grip and pinch task, the target force was set to 50 % of MVC. This value was chosen because several activities involving object manipulation in the hand require this amount of force for effective performance (e.g., holding grocery bags, operating gardening tools, utilising scissors or crafting tools) (Smaby et al., 2004; Neumann and Bielefeld, 2003; Valdes and von der Heyde, 2012). Participants were provided with the target force and grip or pinch force signal on a computer screen placed 1 m in front of them. The graph with the target force line was positioned in the centre of the screen and occupied 70 % of the LabVIEW program front panel. Participants were asked to: "match the target force as accurately as possible and keep the force trace as steady as possible on the target line for 7 s". A 30 s rest was provided between trials for a total of five trials. Signals from each trial were saved to the hard disc for later analyses.

2.7. Data processing and analysis

Force traces were processed in R 3.3.3 (R Core Team, 2017). For the five force matching trials, the central 5 s were analysed. There were three variables of interest (Breedveld, 2004): The root mean square (RMS) error (Zhang et al., 2002), the standard deviation (SD) normalised by participants' MVC (percentage of MVC) (Bagis et al., 2003), and the percent Coefficient of Variation (CoV) of the force signal. Data were statistically analysed using SPSS software version 22 (SPSS, Chicago, IL, USA). Prior to inferential analyses data were screened for normality (Shapiro-Wilk test) and the presence of outliers. Non-normality was observed in some instances. Where possible, reciprocal transformations were used to normalise the distribution of the dependent variables across both groups. Independent samples t-tests were used to test differences between groups in age and height. The Mann-Whitney U was used to analyse weight and body mass index (BMI) differences between groups. Four separate two-way mixed ANOVAs were used to compare the force accuracy and steadiness between groups (between-subjects factor) for the grip and pinch tasks at the first and fifth trial (within-subject factor). In the event of a significant interaction effect, independent t-tests were used to determine where the group difference lay. Correlations between the first force matching trial and pain intensity, DASH and FIHOA scores were assessed visually using scatterplots and Kendall's Tau correlation coefficients were calculated. The alpha-level was set to 0.05 for all analyses. Two-tail tests were utilised across all the analyses.

Fig. 1. Gripping and pinch matching tasks.

3. Results

In total, 88 participants were tested. Table 2 presents participants characteristics. There were no statistically significant between group differences on demographic variables, hand dominance, or the percentage of dominant hands tested. However, grip strength was significantly higher in the control group ($p = 0.03$).

3.1. Force-matching accuracy

The grip strength accuracy for the hand OA and control group at the first and fifth trial is shown in Fig. 2. There was a main effect of time ($F_{1,85} = 19.4$; $p < 0.0001$) and group ($F_{1,85} = 7.7$; $p < 0.01$). In addition, there was an interaction effect between group and time ($F_{1,85} = 4.2$; $p < 0.05$), with significantly lower force matching accuracy in the hand OA group during the first trial ($t_{85} = 3.0$, $p < 0.01$) and no differences between groups in the fifth trial. Pinch force accuracy for both groups is shown in Fig. 3. There was no main effect for group, time, or interaction effect between group and time.

3.2. Force steadiness

The grip force steadiness (SD of force) of the hand OA and control group at the first and fifth trial is shown in Fig. 4. There was a main effect of group ($F_{1,85} = 20.4$; $p < 0.0001$). Grip force steadiness (SD of force) was significantly lower in the hand OA group during the first trial ($t85 = 4.2$, $p < 0.0001$) and the fifth trial ($t85 = 3.2$, $p < 0.01$). There was no main effect for time, or interaction effect between group and time. The grip force steadiness (CoV) of the hand OA and control group at the first and fifth trial is shown in Fig. 5. There was a main effect for group ($F_{1,85} = 12.8$; $p < 0.01$) and time ($F_{1,85} = 8.1$; $p < 0.01$), with a significantly lower grip force steadiness (CoV) in the hand OA group during the first trial ($t85 = 3.0$, $p < 0.01$), and the fifth trial ($t85 = 2.9$, $p < 0.01$). No interaction effect between group and time was identified.

Pinch force steadiness (SD of force) for both groups is shown in Fig. 6. There was a main effect for group ($F_{1,85} = 6.4$; $p < 0.05$), with significantly lower pinch force steadiness (SD of force) in the hand OA group during the first trial ($t85 = 2.7$, $p < 0.01$) but not the fifth trial. There was no main effect for time, or interaction effect between group and time. Pinch force steadiness (CoV) for both groups is shown in Fig. 7. There was a main effect for group ($F_{1,85} = 6.4$; $p < 0.05$), with significantly lower pinch force steadiness in the hand OA group during the first trial ($t85 = 2.5$, $p < 0.05$) but not the fifth trial. There was no main effect for time, or interaction effect between group and time.

3.3. Relationship between force matching ability and measures of pain and function

There was a small correlation ($\tau = 0.2$; $p < 0.05$; $R^2 = 0.06$ to 0.07) between measures of grip force steadiness (SD and CoV) and DASH scores (See Table 3 and Fig. 8). No other significant correlations between grip and pinch force control measures and pain intensity, DASH, or FIHOA measures (all $p > 0.05$) were identified (See Table 3).

Table 2
Participants' characteristics.

	Hand OA ($n = 62$)	Control ($n = 26$)	p values
Age, years	70 (8.5)	70 (11.5)	1.0
Females, *n (%)*	52 (83.9)	18 (69.2)	0.12
Right hand dominant, *n (%)*	55 (88.7)	23 (88.5)	1.0
Dominant hand tested, *n (%)*	39 (63)	17 (65)	0.8
Height, metres	1.65 (0.1)	1.66 (0.08)	0.5
Mass, kg	69.5 (15.3)	70.8 (15.2)	0.9
BMI, kg/m^2	25.4 (4.9)	25.4 (4.4)	0.9
Grip strength, kg	21.6 (8.6)$^+$	25.8 (7.9)$^+$	0.03
Target grip force, kg	10.8 (4.3)	12.9 (4)	–
Pinch strength, kg	3.2 (1.3)	3.5 (1.5)	0.63
Target pinch force, kg	1.6 (0.65)	1.75 (0.75)	–
DASH	28.4 (15.9)	–	–
FIHOA	8.3 (5.6)	–	–
Bilateral hand pain, n (%)	13 (21.0)	–	–
Number of painful joints, n	5.1 (3.9)	–	–
Average hand pain, NRS *	4.2 (2.2)	–	–
Duration of pain, years	9.5 (9.1)	–	–

Note: All values are mean (SD) unless otherwise specified. n = number of participants; BMI = body mass index;+= statistically significant difference between groups, $p < 0.05$; NRS = numerical pain rating scale (0–10, where 0 = no pain and 10 = worst pain you can imagine); * = in most painful hand.

4. Discussion

The present study identified submaximal force control impairments in people with symptomatic hand OA compared to healthy controls. In particular, people with hand OA presented with lower grip but not pinch force-matching accuracy compared to healthy controls. In addition, lower grip and pinch force steadiness was identified in people with hand OA. A small correlation was identified between measures of grip force control and self-reported measures of hand function (DASH), however, no association with average hand pain was shown. A learning effect was apparent in the hand OA group with larger force control impairments during the 1st trial which were resolved by the 5th trial.

The ability to accurately match a target force and maintain a steady muscle contraction have been shown to progressively worsen across the life span and may be further impaired in chronic musculoskeletal conditions such as osteoarthritis. In the hand, it has been noted that older people present with ~50 % deficits in pinch force tracking ability compared to young adults (Godde et al., 2018). People with thumb OA have also been shown to present with worse dynamic stability during very low load (≈300 g) tip to tip pinch tasks, compared to healthy controls (Lawrence et al., 2014; Valero-Cuevas et al., 2003). Furthermore, in people with knee OA, quadriceps' force steadiness has been shown to be twice as large as in healthy controls (Hortobagyi et al., 2004). The current study provides additional evidence of deficits in submaximal grip force accuracy in people with hand OA, with ~50 % greater errors compared to controls during grip force-matching tasks when performing the task for the 1st time. Similarly, hand OA

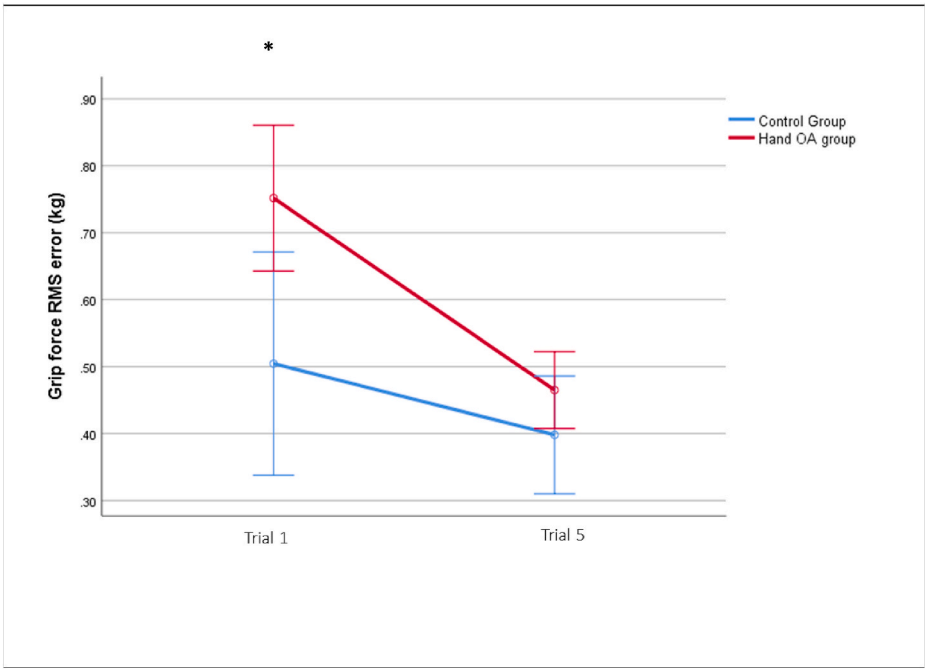

Fig. 2. Grip force-matching accuracy (RMS error) at the first and fifth trial. Means and 95 % CI are shown. * = $p < 0.01$.

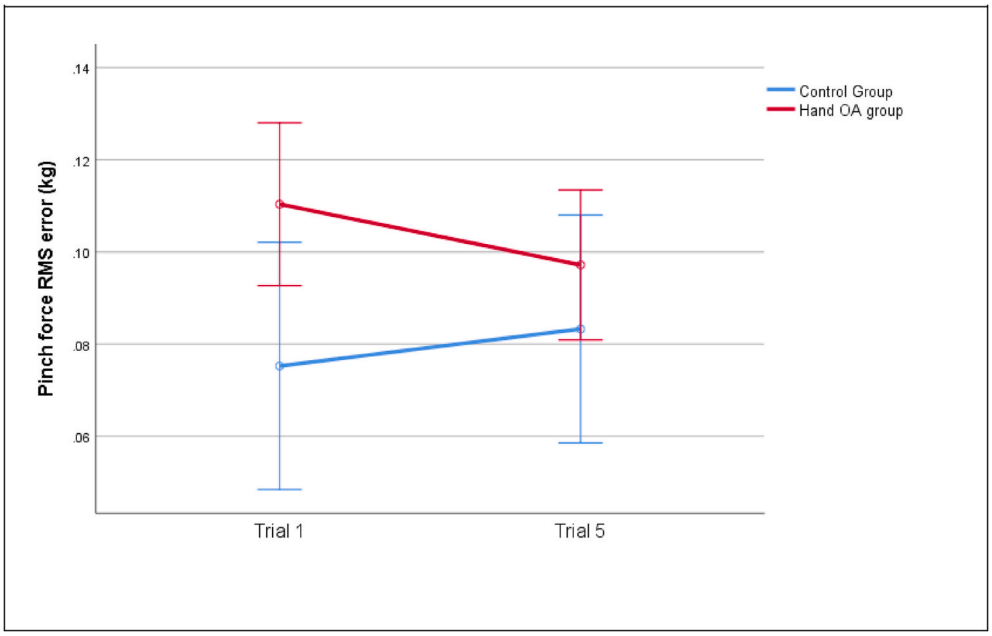

Fig. 3. Pinch force-matching accuracy (RMS error) at the first and fifth trial. Means and 95 % CI are shown.

participants presented with a ~70–80 % deficit in grip force steadiness and ~35–50 % deficit in pinch force steadiness compared to healthy controls. While there was a ~30 % deficit in pinch force accuracy between groups, this did not reach statistical significance, possibly due to large variability during the first trial in the control group.

The mechanisms explaining these deficits are unclear and were beyond the scope of the current study. However, it is possible that there are intramuscular and intermuscular effects that influence force accuracy and steadiness. From an intramuscular perspective, it has been shown that motor unit discharge rate variability contributes to fluctuations in force modulation (Kornatz et al., 2005). In healthy individuals, experimentally induced peri-articular knee pain has been shown to impair force steadiness (Rice et al., 2015) with two studies reporting greater variability in motor unit discharge within the same muscle when participants are exposed to experimentally induced pain compared to a no pain condition (Tucker and Hodges, 2010; Poortvliet et al., 2015). Furthermore, a correlation between quadriceps' force matching accuracy and average knee pain has been observed in people with knee OA by Shanahan et al. (2015). These neuromuscular changes could be driven by group III and IV afferent inputs, which may inhibit motoneuron discharge (Tucker and Hodges, 2010) and disrupt proprioceptive signals from the muscle spindle (Capra and Ro, 2000) or golgi tendon organs (Proske and Allen, 2019). However, in the current study, no relationship between average hand pain and measures of force control

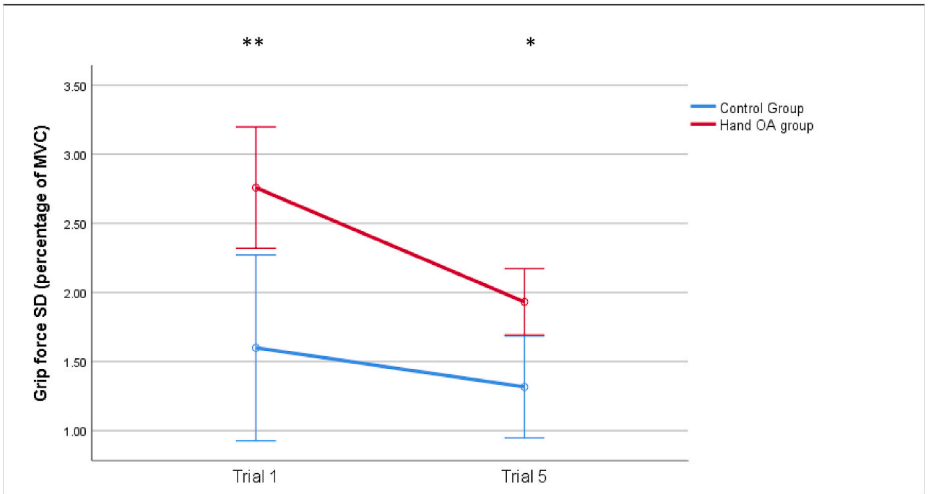

Fig. 4. Grip force steadiness (SD of force) at the first and fifth trial. Means and 95 % CI are shown. ** = $p < 0.0001$; *$p < 0.01$.

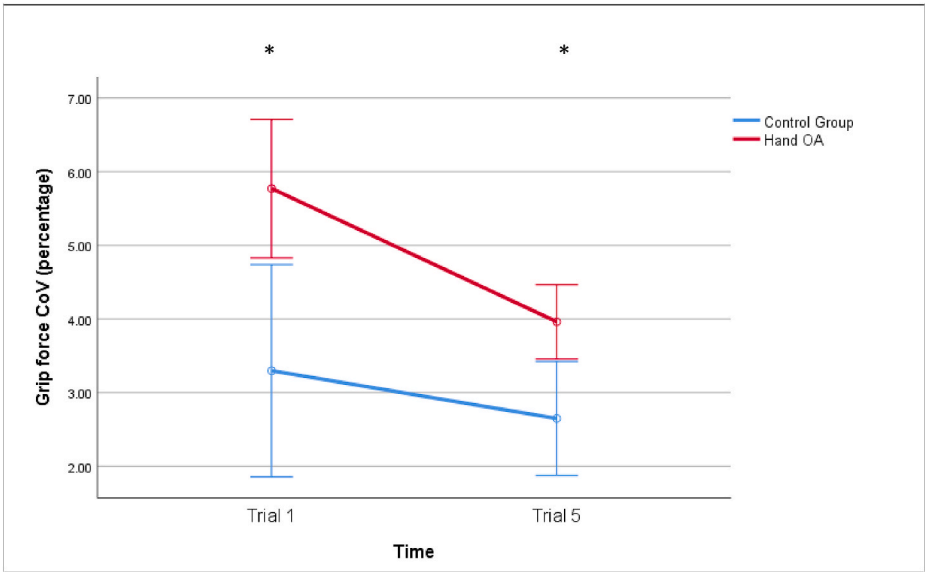

Fig. 5. Grip force steadiness (CoV) at the first and fifth trial. Means and 95 % CI are shown. * = $p < 0.01$.

were observed. With respect to movement and force control, the hand has many more degrees of freedom compared to the knee joint, possibly leading to execution of the force matching task by utilising alternative muscle recruitment strategies. This, combined with the heterogeneity of our sample in both the location and number of painful joints affected, may have contributed to the lack of a relationship between hand pain (measured as the average across all joints) and force control in our cohort.

Intermuscular effects may also influence force accuracy and steadiness. In particular lack of coordination between agonist and antagonists may contribute to these impairments. For example, during a novel hand movement task, post stroke patients have been shown to have a low agonist-antagonist coordination (Jian et al., 2020). With training, the activity of antagonist muscle has been shown to reduce, with an overall improvement in hand coordination (Jian et al., 2020; Balshaw et al., 2019). More speculatively, intermuscular changes could also be due to impairments of the sensory and motor cortices, which have been shown to undergo neuroplastic remodeling in various chronic pain conditions (Lima and Fregni, 2008; Kutch et al., 2017; Kutch and Tu, 2016).

Of interest, the impairments in force control we observed in people with hand OA were greatest during the 1st trial and improved with practice, approaching the performance of control participants after 5 trials. Similarly, large initial errors and rapid improvements in finger twitch direction accuracy have been noted in people with hand arthritis during a novel motor learning task (Parker et al., 2017). Furthermore, at the knee joint improvements were reported by Hortobagyi et al. (2001) over the first ten trials of a quadriceps force matching task. The mechanisms explaining such a rapid improvement in force control are unclear and were beyond the scope of the current study. However, previous research (Parker et al., 2017) has demonstrated reduced levels of resting intracortical inhibition in the primary motor cortex of people with chronic hand arthritis. As a reduction in primary motor cortex intracortical inhibition is closely related to successful motor learning (Amadi et al., 2015; Dumel et al., 2018), it may be that such a loss of inhibition in people with hand OA facilitates rapid learning of a novel motor task (Parker et al., 2017).

Impaired force control in people with hand OA may be relevant for clinical practice in light of its relationship to hand function. In particular, we identified a small positive correlation between grip strength force matching accuracy and the DASH score ($\tau = 0.2$; $p < 0.05$). This suggests that impaired grip force control is associated with worse self-reported function. However, impairments in force control only

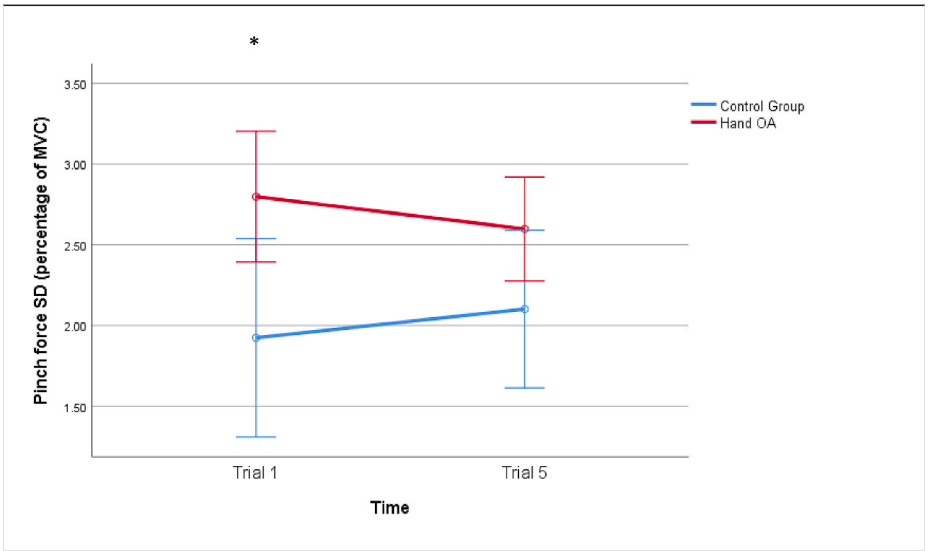

Fig. 6. Pinch force steadiness (SD of force) at the first and fifth trial. Means and 95 % CI are shown. * = $p < 0.01$.

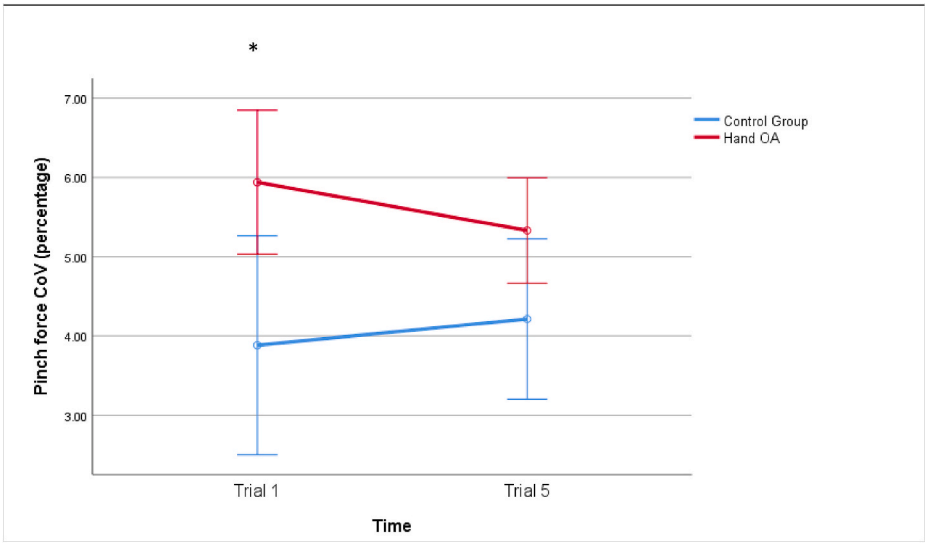

Fig. 7. Pinch force steadiness (CoV) at the first and fifth trial. Means and 95 % CI are shown. * = $p < 0.05$.

Table 3
Correlation (Kendall's Tau) for force control measures (Trial 1), and pain and function.

Force control measures	Average pain (SF-BPI)	DASH	FIHOA
Grip force RMS error	−0.02	0.05	−0.02
Grip force SD	0.03	0.2*	0.09
Grip force CoV	0.02	0.2*	0.09
Pinch force RMS error	−0.14	0.02	−0.07
Pinch force SD	0.05	0.07	−0.06
Pinch force CoV	−0.05	0.08	−0.05

Note. DASH = disability of the arm shoulder and hand questionnaire; FIHOA = functional index of hand osteoarthritis; SF-BPI = brief pain inventory short form; RMS = root mean square; SD = standard deviation; *$p < 0.05$.

explained a small percentage (6–7%) of the DASH score variance. One study (Nunes et al., 2012) has previously show a strong relationship between measures of motor control and the DASH ($r = 0.7$) in people with hand OA. More specifically, Nunes et al. (2012) noted that greater grip force at object lift off, and greater latency (ms) between gripping and lifting an object, were associated with higher levels of self-reported disability. In respect to pinch force control measures, we identified no association with functional outcome. It has been previously suggested by Smaby et al. (2004) that the inability to fine tune the direction of forces, rather than the magnitude, may be responsible for functional deficits during pinching tasks. Interestingly, these findings are consistent with other research suggesting that dynamic stability during pinching (the ability to stabilise an inherently unstable system at very low loads) contributes significantly to hand function (Lawrence et al., 2015). Research with knee and hip OA participants has shown that force steadiness and force matching error are associated with performance based tasks such as timed stair climbing tests (Hortobagyi et al., 2004; Pua et al., 2010) and chair-rise time (Hortobagyi et al., 2004; Seynnes et al., 2005). In this regard, in healthy older adults, it has been shown that training induced reductions in motor fluctuations are strongly correlated with improvements in hand dexterity measured by the Purdue Pegboard Test (Kornatz et al., 2005). It is therefore plausible that people with symptomatic hand OA may benefit from performing task specific repetitions in preparation of fine motor skill activities (e.g. doing buttons, using a zipper, soldering, painting) (Smaby et al., 2004).

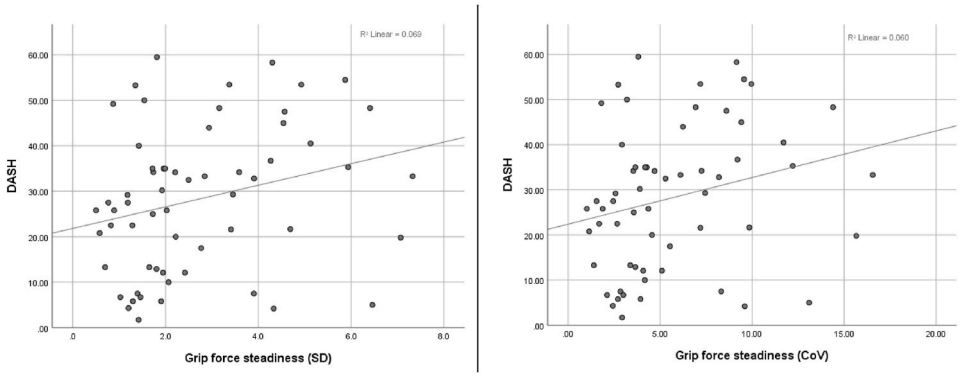

Fig. 8. Visual representation of correlation between Grip force steadiness (SD and CoV at trial 1) and DASH.

Further research is required to assess this point.

4.1. Limitations

The current study assessed force-matching error and steadiness at a relative percentage of MVC. Other studies have chosen to compare measures of force control at an absolute level of force instead (Hortobagyi et al., 2001). However, a relative percentage approach may be more appropriate, as it takes into account individuals' strength variations, which could be a counfounding factor when comparing different groups (Yoon et al., 2014). During the data collection process, MVC was assessed prior to the force matching tasks. It is therefore possible that this led to a temporary increase in hand pain. However, a 5 min rest was provided between MVC and force control assessments, visual assessments of the MVC were not indicative of pain affecting force production, and no participants commented upon discomfort during or after the task. Furthermore, previous research has shown that grip strength testing leads to small, clinically unimportant changes in pain in people with rheumatoid arthritis (Kennedy et al., 2010). Another potential limitations is the heterogeneity of the OA study population, which included anyone with both radiographic and clinical evidence of hand OA, irrespective of the joint(s) affected (i.e., 1st cmcj OA, ipj and wrist OA). It is possible that different hand OA phenotypes present with distinct motor control impairments. For example, it could be hypothesised that pinch force control may be particularly impaired in people with 1st CMC OA. Future studies may wish to examine these relationships in more detail.

5. Conclusions

This study adds to the growing body of evidence showing impaired submaximal force control in individuals with hand OA. Specifically, when first performing force matching tasks, people with hand OA presented with higher force-matching error in gripping tasks compared to healthy controls and reduced force steadiness during gripping and pinching. These impairments improved with practice. There was also a small but significant correlation between initial force control impairments and the DASH. No correlation was identified between initial force control and other measures of hand function or pain. Future studies might examine whether objective performance based measures of hand function and dexterity are associated with submaximal force control in people with hand OA.

Acknowledgement

Part of the data collection was funded through a Physiotherapy New Zealand Grant.

References

Allen, D., Barnett, F., 2011. Reliability and validity of an electronic dynamometer for measuring grip strength. Int. J. Ther. Rehabil. 18 (5), 258–264.
Altman, R.D., Alarcon, G., Appelrouth, D., Bloch, D., Borenstein, D., Brandt, K., et al., 1990. The American College of Rheumatology criteria for the classification and reporting of osteoarthritis of the hand. Arthritis Rheum. 33 (11), 1601–1610.
Amadi, U., Allman, C., Johansen-Berg, H., Stagg, C.J., 2015. The homeostatic interaction between anodal transcranial direct current stimulation and motor learning in humans is related to GABAA activity. Brain Stimul. 8 (5), 898–905.
Bagis, S., Sahin, G., Yapici, Y., Cimen, O.B., Erdogan, C., 2003. The effect of hand osteoarthritis on grip and pinch strength and hand function in postmenopausal women. Clin. Rheumatol. 22 (6), 420–424.
Baker, V., Bennell, K., Stillman, B., Cowan, S., Crossley, K., 2002. Abnormal knee joint position sense in individuals with patellofemoral pain syndrome. J. Orthop. Res. 20 (2), 208–214.
Balshaw, T.G., Massey, G.J., Maden-Wilkinson, T.M., Lanza, M.B., Folland, J.P., 2019. Neural adaptations after 4 years vs 12 weeks of resistance training vs untrained. Scand. J. Med. Sci. Sports 29 (3), 348–359.
Beaton, D.E., Katz, J.N., Fossel, A.H., Wright, J.G., Tarasuk, V., Bombardier, C., 2001. Measuring the wole or the parts? Validity, reliability, and responsiveness of the disabilities of the arm, shoulder and hand outcome measure in different regions of the upper extremity. J. Hand Ther. 14 (2), 128–142.
Breedveld, F.C., 2004. Osteoarthritis: the impact of a serious disease. Rheumatology 43 (Suppl. 1), 4–8.
Capra, N.F., Ro, J.Y., 2000. Experimental muscle pain produces central modulation of proprioceptive signals arising from jaw muscle spindles. Pain 86 (1–2), 151–162.
Carment, L., Abdellatif, A., Lafuente-Lafuente, C., Pariel, S., Maier, M.A., Belmin, J., et al., 2018. Manual dexterity and aging: a pilot study disentangling sensorimotor from cognitive decline. Front. Neurol. 9 (910).
de Oliveira, D.G., Nunes, P.M., Aruin, A.S., Dos Santos, M.J., 2011. Grip force control in individuals with hand osteoarthritis. J. Hand Ther. 24 (4), 345–354.
Dumel, G., Bourassa, M.-È., Charlebois-Plante, C., Desjardins, M., Doyon, J., Saint-Amour, D., et al., 2018. Multisession anodal transcranial direct current stimulation induces motor cortex plasticity enhancement and motor learning generalization in an aging population. Clin. Neurophysiol. 129 (2), 494–502.
Faul, F., Erdfelder, E., Lang, A.G., Buchner, A.G., 2007. Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences [Internet] Behav. Res. Methods 39 (2), 91–175. Available from: http://www.springer.com/psychology/cognitive+psychology/journal/13428.
Gerodimos, V., Karatrantou, K., Psychou, D., Vasilopoulou, T., Zafeiridis, A., 2017. Static and dynamic handgrip strength endurance: test-retest reproducibility. J Hand Surg Am 42 (3), e175–e184.
Godde, B., Trautmann, M., Erhard, P., Voelcker-Rehage, C., 2018. Motor practice in a force modulation task in young and middle-aged adults. J. Electromyogr. Kinesiol. 38, 224–231.
Holmström, L., de Manzano Ö, Vollmer, B., Forsman, L., Valero-Cuevas, F.J., Ullén, F., et al., 2011. Dissociation of brain areas associated with force production and stabilization during manipulation of unstable objects. Exp. Brain Res. 215 (3), 359–367.
Hortobagyi, T., Tunnel, D., Moody, J., Beam, S., DeVita, P., 2001. Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. J Gerontol A Biol Sci Med Sci 56 (1), B38–B47.
Hortobagyi, T., Garry, J., Holbert, D., Devita, P., 2004. Aberrations in the control of quadriceps muscle force in patients with knee osteoarthritis. Arthritis Rheum. 51 (4), 562–569.
Jian, C., Deng, L., Liu, H., Yan, T., Wang, X., Song, R., 2020. Modulating and restoring inter-muscular coordination in stroke patients using two-dimensional myoelectric computer interface: a cross-sectional and longitudinal study. J. Neural. Eng. 18 (3).
Kennedy, D., Jerosch-Herold, C., Hickson, M., 2010. The reliability of one vs. three trials of pain-free grip strength in subjects with rheumatoid arthritis. J. Hand Ther. : Off. J. Am. Soc. Hand Ther. 23 (4), 384–390 quiz 91.

Kornatz, K.W., Christou, E.A., Enoka, R.M., 2005. Practice reduces motor unit discharge variability in a hand muscle and improves manual dexterity in old adults. J. Appl. Physiol. 98 (6), 2072–2080. Bethesda, Md : 1985.
Kutch, J.J., Tu, F.F., 2016. Altered brain connectivity in dysmenorrhea: pain modulation and the motor cortex. Pain 157 (1), 5–6.
Kutch, J.J., Ichesco, E., Hampson, J.P., Labus, J.S., Farmer, M.A., Martucci, K.T., et al., 2017. Brain signature and functional impact of centralized pain: a multidisciplinary approach to the study of chronic pelvic pain (MAPP) network study. Pain 158 (10), 1979–1991.
Laidlaw, D.H., Kornatz, K.W., Keen, D.A., Suzuki, S., Enoka, R.M., 1999. Strength training improves the steadiness of slow lengthening contractions performed by old adults. J. Appl. Physiol. 87 (5), 1786–1795. Bethesda, Md : 1985.
Lawrence, E.L., Fassola, I., Werner, I., Leclercq, C., Valero-Cuevas, F.J., 2014. Quantification of dexterity as the dynamical regulation of instabilities: comparisons across gender, age, and disease. Front. Neurol. 5, 53.
Lawrence, E.L., Dayanidhi, S., Fassola, I., Requejo, P., Leclercq, C., Winstein, C.J., et al., 2015. Outcome measures for hand function naturally reveal three latent domains in older adults: strength, coordinated upper extremity function, and sensorimotor processing. Front. Aging Neurosci. 7, 108.
Lima, M.C., Fregni, F., 2008. Motor cortex stimulation for chronic pain: systematic review and meta-analysis of the literature. Neurology 70 (24), 2329–2337.
Magni, N.E., McNair, P.J., Rice, D.A., 2018. Sensorimotor performance and function in people with osteoarthritis of the hand: a case-control comparison. Semin. Arthritis Rheum. 47 (5), 676–682.
Mendoza, T., Mayne, T., Rublee, D., Cleeland, C., 2006. Reliability and validity of a modified Brief Pain Inventory short form in patients with osteoarthritis. Eur. J. Pain 10 (4), 353.
Moe, R.H., Garratt, A., Slatkowsky-Christensen, B., Maheu, E., Mowinckel, P., Kvien, T. K., et al., 2010. Concurrent evaluation of data quality, reliability and validity of the Australian/Canadian osteoarthritis hand index and the functional index for hand osteoarthritis. Rheumatology 49 (12), 2327–2336.
Mosier, K., Lau, C., Wang, Y., Venkadesan, M., Valero-Cuevas, F.J., 2011. Controlling instabilities in manipulation requires specific cortical-striatal-cerebellar networks. J. Neurophysiol. 105 (3), 1295–1305.
Neumann, D.A., Bielefeld, T., 2003. The carpometacarpal joint of the thumb: stability, deformity, and therapeutic intervention. J. Orthop. Sports Phys. Ther. 33 (7), 386–399.
Nunes, M.P., de Oliveira, D., Aruin, A.S., Dos Santos, J.M., 2012. Relationship between hand function and grip force control in women with hand osteoarthritis. J. Rehabil. Res. Dev. 49 (6), 855–865.
R Core Team. R, 2017. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Parker, R.S., Lewis, G.N., Rice, D.A., McNair, P.J., 2017. The association between corticomotor excitability and motor skill learning in people with painful hand arthritis. Clin. J. Pain 33 (3), 222–230.
Poortvliet, P.C., Tucker, K.J., Hodges, P.W., 2015. Experimental pain has a greater effect on single motor unit discharge during force-control than position-control tasks. Clin. Neurophysiol. 126 (7), 1378–1386.
Proske, U., Allen, T., 2019. The neural basis of the senses of effort, force and heaviness. Exp. Brain Res. 237 (3), 589–599.
Proske, U., Gandevia, S.C., 2012. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. Physiol. Rev. 92 (4), 1651–1697.
Pua, Y.H., Clark, R.A., Bryant, A.L., 2010. Physical function in hip osteoarthritis: relationship to isometric knee extensor steadiness. Arch. Phys. Med. Rehabil. 91 (7), 1110–1116.
Rice, D.A., McNair, P.J., Lewis, G.N., Mannion, J., 2015. Experimental knee pain impairs submaximal force steadiness in isometric, eccentric, and concentric muscle actions. Arthritis Res. Ther. 17 (1), 259.
Salahzadeh, Z., Maroufi, N., Salavati, M., Aslezaker, F., Morteza, N., Rezaei Hachesu, P., 2013. Proprioception in subjects with patellofemoral pain syndrome: using the sense of force accuracy. J. Muscoskel. Pain 21 (4), 341–349.
Schabrun, S.M., Hodges, P.W., 2012. Muscle pain differentially modulates short interval intracortical inhibition and intracortical facilitation in primary motor cortex. J. Pain : Off. J. Am. Pain Soc. 13 (2), 187–194.
Seynnes, O., Hue, O.A., Garrandes, F., Colson, S.S., Bernard, P.L., Legros, P., et al., 2005. Force steadiness in the lower extremities as an independent predictor of functional performance in older women. J. Aging Phys. Activ 13 (4), 395–408.
Shanahan, C.J., Hodges, P.W., Wrigley, T.V., Bennell, K.L., Farrell, M.J., 2015. Organisation of the motor cortex differs between people with and without knee osteoarthritis. Arthritis Res. Ther. 17 (1), 164.
Smaby, N., Johanson, M.E., Baker, B., Kenney, D.E., Murray, W.M., Hentz, V.R., 2004. Identification of key pinch forces required to complete functional tasks. J. Rehabil. Res. Dev. 41 (2), 215–224.
Trampisch, U.S., Franke, J., Jedamzik, N., Hinrichs, T., Platen, P., 2012. Optimal jamar dynamometer handle position to assess maximal isometric hand grip strength in epidemiological studies. J. Hand Surg. 37 (11), 2368–2373.
Tucker, K.J., Hodges, P.W., 2010. Changes in motor unit recruitment strategy during pain alters force direction. Eur. J. Pain 14 (9), 932–938.
Valdes, K., von der Heyde, R., 2012. An exercise program for carpometacarpal osteoarthritis based on biomechanical principles. J. Hand Ther. 25 (3), 251–263.
Valero-Cuevas, F.J., Smaby, N., Venkadesan, M., Peterson, M., Wright, T., 2003. The strength-dexterity test as a measure of dynamic pinch performance. J. Biomech. 36 (2), 265–270.
Villafañe, J.H., Valdes, K., 2014. Reliability of pinch strength testing in elderly subjects with unilateral thumb carpometacarpal osteoarthritis. J. Phys. Ther. Sci. 26 (7), 993–995.
Yoon, T., Vanden Noven, M.L., Nielson, K.A., Hunter, S.K., 2014. Brain areas associated with force steadiness and intensity during isometric ankle dorsiflexion in men and women. Exp. Brain Res. 232 (10), 3133–3145.
Zhang, Y., Niu, J., Kelly-Hayes, M., Chaisson, C.E., Aliabadi, P., Felson, D.T., 2002. Prevalence of symptomatic hand osteoarthritis and its impact on functional status among the elderly: the Framingham Study. Am. J. Epidemiol. 156 (11), 1021–1027.