Normative values of isometric elbow strength in healthy adults: a systematic review

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Abstract

Background: Post-traumatic deformities such as biceps tendon rupture or (peri-)articular fractures of the elbow are often related to a decrease in muscle strength. Postoperative evaluation of these deformities requires normative values of elbow strength. The purpose of this systematic review was to determine these normative values of isometric elbow strength in healthy adults resulting from studies evaluating this strength (i.e. flexion, extension, pronation and supination strength).

Methods: The databases of PubMed, EMBASE and Web of Sciences were searched and screened for studies involving the isometric elbow strength as measured in asymptomatic volunteers. The quality of the studies was assessed and studies of low quality were excluded.

Results: Nineteen studies met the inclusion criteria and were of sufficiently high quality to be included in the present review. In these studies, elbow strength was measured in a total of 1880 healthy volunteers. The experimental set-up and devices used to measure elbow strength varied between studies. Using some assumptions, a normative values table was assembled.

Conclusions: Large standard deviations of normative values in combination with different measurement devices used, as well as the different measurement positions of the subjects, demonstrated that there is no consensus about measuring the isometric elbow strength and therefore the normative values have to be interpreted with caution.

Keywords

elbow extension, elbow flexion, isometric elbow strength, pronation, supination, systematic review

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Introduction

The range of motion of the elbow has always been a topic of interest in elbow related scientific research. Because technology in daily life with respect to mobile phones, game controllers and curling irons is becoming more and more advanced, an optimal range of motion, especially flexion and pronation, appears to be more important than ever.¹ The range of motion of the elbow joint can be restricted by disease, injury or disuse.^{2,3} The same accounts for the muscle strength of the upper extremity.^{4–6} It is important to know the initial strength of patients or, in the case of an absence of this strength, the normative values. This should provide patients with an insight into their decrease in

strength and give them an objective goal to reach their initial strength after rehabilitation. These normative values are not clearly reported in the existing literature. Using the normative values, it is possible to determine the ratio between the dominant and the

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nondominant arm. This ratio would allow the use of the contralateral side of the patients as reference value.⁷

The aim of this systematic review is therefore to determine the normative values of the isometric elbow strength of healthy adults. The values are a result of the available studies that evaluated either (or both) the isometric flexion–extension strength of the elbow or the isometric pronation–supination strength of the forearm in terms of the ratio between the dominant and nondominant arm.

Materials and methods

Identification of studies and selection criteria

A literature search was performed using the databases Pubmed, EMBASE and Web of Sciences on 4 May 2016. The search was performed by searching in MeSH (medical subject headings) search terms and title and abstracts. Included in the search were the following terms and their synonyms: ‘elbow’ OR ‘forearm’, ‘muscle strength’ OR ‘isometric contraction’, ‘reference value’ OR ‘healthy volunteer’, as well as the elbow movements (i.e. flexion, extension, pronation and supination). The search strategy is presented in Appendix 1. Because the movement of the elbow has always spiked interests in the academic field, no limitation on the publication date was set. Duplicates were removed from the search. The remaining articles resulting from the literature search were reviewed on their titles and abstracts to identify possible relevant publications. All potential relevant literature underwent a full review aiming to determine whether they met the inclusion criteria. Studies that did not meet the inclusion criteria after reading the full manuscript were excluded from the present study. The reference lists of the included papers were checked manually to identify possible other relevant studies that could be included in the present study but were missed in the initial search. The inclusion and exclusion of the studies was performed independently by two of the investigators (SK and JV). In the case of discrepancy, a consensus was reached between the two investigators.

To be included in the present study, the full texts of the articles had to be available. Only English, Dutch, German and French literature was included; studies in other languages were excluded. The articles included had to describe the measurement of the isometric muscle strength of the elbow (flexion, extension, pronation and/or supination) with a dynamometer or other device in healthy adult volunteers without any intervention.

Quality assessment

The methodological quality of all the included studies was assessed by two of the reviewers at the study level. The quality of the studies was assessed by means of Table 1. The main topics of the check involved the position of the subjects measured, the device used for measurements, the measurement itself, and the study population. When articles received three or more minuses, the publication considered not to be of sufficiently high quality to be included in the present systematic review.

Outcome measures and data extraction

The primary outcome of this systematic review is elbow strength; in particular, the flexion–extension strength of the elbow and the pronation–supination strength of the forearm. The strength of these movements were presented in different units (e.g. Nm, kg/cm and N). Secondary outcomes were the position of the subjects (with respect to body/shoulder/elbow/forearm), the measurement devices used to measure the isometric elbow strength, the measurements used in the analysis (defined as the average/highest value), the population used to determine the elbow strength, the elbow movement over which the strength was determined, and the actual elbow strength measured in those studies. The actual elbow strength could consist of the strengths of men and women, as well as the dominant and nondominant arms.

Statistical analysis

Descriptive statistics are reported in the results; these include the mean (SD) values. These statistics were directly transferred out of the included studies or determined using the results from the included studies. Overall mean (SD) values were created using the SPSS, version 21.0 (IBM Corp., Armonk, NY, USA). The normative values were determined using the means of the included studies weighted by the number of subjects included in the study.

Results

Study identification

The systematic search yielded a total of 3374 articles (Fig. 1). After the duplicates were removed, 2420 studies remained, which were screened based on title and abstract. Screening resulted in 31 articles that were selected for full text assessment. The full text assessment concluded that seven more articles had to be excluded for various reasons. This resulted in 24 articles

Table 1. Methodological quality checked regarding the position of the subject, the measurement device, the measurement itself and the population studied.

Topic		Categories			Explanation
1	Position of subject described	Yes (+)	No (–)	Not clear (?)	Sitting/standing/prone/supine
2	Position of the shoulder described	Yes (+)	No (–)	Not clear (?)	Degrees of flexion/extension/abduction/adduction
3	Position of the elbow described	Yes (+)	No (–)	Not clear (?)	Degrees of flexion/extension
4	Position of the forearm described	Yes (+)	No (–)	Not clear (?)	Neutral/degrees pronated/supinated
5	Isometric strength measurement	Yes (+)	No (–)	Not clear (?)	
6	Measurement device described	Yes (+)	No (–)	Not clear (?)	Commercial dynamometer/custom made dynamometer/other
7	Validation or calibration of the instrument	Yes (+)	No (–)	Not mentioned (?)	*Corresponding author contacted, until submitting no response
8	Measurement repeated	Yes (+)	No (–)	Not clear (?)	≥ 2 measurements = yes/ 1 measurement = no
9	Was the sample size adequate?	Yes (+)	No (–)		> 50 subjects = yes/ < 50 subjects = no
10	Sex of the population described	Yes (+)	No (–)		Male/female
11	Age of the population described	Yes (+)	No (–)		Mean age/age range
12	Arm dominance of the population described/analyzed	Yes (+)	No (–)		Left/right dominant arm

for which the methodological quality was assessed (Appendix 2). Finally, from the total of 3374 articles found in the initial literature search, 19 articles met the inclusion criteria and were of sufficiently high quality to be included in the present review.

Outcomes

Appendix 3 shows the results of the included studies, and also provides details of the characteristics of the studies together with the strengths found in each study. These studies were published between 1951 and 2014 and included a total of 1880 healthy adults (1179 men and 701 women). The included studies had a mean sample size of 98.95 (124.8) healthy adults (range 3 to 462) with a mean age of 37.8 (12.6) years (range 15 years to 83 years). Of these 19 studies, seven articles studied the differences between the men and women and 12 between the dominant and nondominant arm. In these 19 studies, different measurement devices were used resulting in different results with different measuring units. As a result of these different measuring units,

it was only possible to compare the results with the studies for which the outcome measures could be converted into each other (Appendix 3). To compare all the of the results, they were converted into Nm by multiplying the strengths with the moment arm for flexion–extension (26.4 cm, which is the average forearm length according to Askew et al.⁸) and the moment arm for pronation–supination (6.7 cm, which is an average of the epicondyle width of Askew et al.⁸). The results are still an estimation of the converted results, although they can be compared with each other by considering the different measurement devices and the different positions of the subjects used. The results of this estimation are presented in Table 2.

Flexion and extension strength of the elbow

Of the included studies, six articles studied only the flexion strength in asymptomatic volunteers. In addition, six other studies investigated the flexion strength together with the extension strength. This led to a total of 12 studies that evaluated the flexion strength of the

Figure 1. Flowchart of the systematic search strategy used.³⁴

elbow, resulting in a total of 1552 healthy volunteers who had their elbow flexion strength measured. As noted earlier, six studies studied the extension strength together with the flexion strength of the elbow. The extension strength was measured in a total of 846 healthy adults.

The mean (SD) values of the estimated normative strength of the elbow weighted by the number of subjects were determined and are presented in Table 3 using descriptive statistics, as well as by weighting the cases by the number of subjects included. The ratios of the differences between the dominant and nondominant arms per movement are also presented in this table.

Pronation and supination

Two studies, which evaluated the flexion and extension strength of the elbow, also determined the pronation

and supination strength of the forearm. In addition to these two studies, seven other studies evaluated the pronation–supination strength in healthy individuals. These nine studies resulted in a total of 472 asymptomatic volunteers, who were measured with different devices, resulting in strengths with different units of measurement. The results of the averaged but weighted cases of the pronation–supination strength are presented in Table 3.

Discussion

The present systematic review has made an overview of studies reporting on elbow strength (flexion, extension, pronation, supination) because there is no consensus on the normative values of the isometric elbow strength. Using the databases of Pubmed, EMBASE and the Web of Science, the results of 19 studies were included

Table 2. Estimated results of the included studies converted in order to be able to compare the strengths with each other.

Study	Flexion	Extension	Pronation	Supination
Andrews et al. ¹⁸	Dom: • Male: 69.2 (11.9) Nm • Female: 40.6 (7.4) Nm Ndom: • Male: 66.2 (6.7) Nm • Female: 39.8 (6.7) Nm	Dom: • Male: 44.4 (9.5) Nm • Female: 26.1 (5.7) Nm Ndom: • Male: 43.0 (8.5) Nm • Female: 25.6 (5.5) Nm		
Askew et al. ⁸	Dom: • Male: 71.1 (15.1) Nm • Female: 33.0 (7.8) Nm Ndom: • Male: 69.4 (15.3) Nm • Female: 31.7 (7.6) Nm	Dom: • Male: 41.3 (10.7) Nm • Female: 20.6 (6.0) Nm Ndom: • Male: 39.8 (10.4) Nm • Female: 19.0 (4.9) Nm	Dom: • Male: 7.2 (1.8) Nm • Female: 3.5 (0.8) Nm Ndom: • Male: 6.7 (1.7) Nm • Female: 3.2 (1.0) Nm	Dom: • Male: 8.9 (2.3) Nm • Female: 4.3 (1.2) Nm Ndom: • Male: 7.8 (2.1) Nm • Female: 4.0 (1.0) Nm
Balogun and Onigbinde ¹⁹	Dom: • Right: 71.7 (16.8) Nm • Left: 69.1 (15.5) Nm			
Bohannon ²⁰	Dom: • Ametek: 59.9 (18.6) Nm • Chatillon: 55.3 (17.4) Nm Ndom: • Ametek: 58.6 (17.3) Nm • Chatillon: 54.5 (16.2) Nm			
Bohannon and Saunders ²¹	60.5 (19.4) Nm			
Coombes et al. ²²	49.1 (8.5) Nm	64.9 (10.7) Nm		
Darcus ²³			2.1 Nm	1.3 Nm
Douma et al. ²⁴	Dom: 71.8 (13.8) Nm Ndom: 68.2 (13.1) Nm	Dom: 48.5 (12.2) Nm Ndom: 47.1 (10.7) Nm		
Harbo et al. ²⁵	Dom • Male: 50.9 (13.6) Nm • Female: 26.5 (5.6) Nm			
Herzberg et al. ^{(*)26}			• Male: 4.9 Nm • Female: 2.5 Nm • Dom: 3.8 Nm • Ndom: 3.1 Nm	• Male: 5.3 Nm • Female: 3.8 Nm • Dom: 4.0 Nm • Ndom: 3.6 Nm
Kramer et al. ²⁷			BTE: • Dom o Male: 11.8 (3.6) Nm o Female: 6.2 (1.5) Nm • Ndom: o Male: 10.8 (3.3) Nm o Female: 5.6 (1.2) Nm Cybex: • Dom o Male: 12.6 (3.2) Nm o Female: 7.2 (1.9) Nm • Ndom o Male: 12.8 (2.9) Nm o Female: 6.9 (1.7) Nm	BTE: • Dom o Male: 10.7 (3.3) Nm o Female: 5.7 (1.4) Nm • Ndom o Male: 10.0 (3.0) Nm o Female: 5.3 (1.0) Nm Cybex: • Dom o Male: 10.6 (2.5) Nm o Female: 5.7 (1.2) Nm • Ndom o Male: 10.1 (2.2) Nm o Female: 5.5 (1.4) Nm
Matsuoka et al. ¹⁶			Dom: • Male: 10.0 (3.6) Nm • Female: 5.1 (1.6) Nm	Dom: • Male: 7.4 (3.2) Nm • Female: 3.8 (0.9) Nm

(continued)

Table 2. Continued

Study	Flexion	Extension	Pronation	Supination
			Ndom: • Male: 9.1 (3.7) Nm • Female: 4.2 (1.3) Nm	Ndom: • Male: 6.9 (2.5) Nm • Female: 3.8 (0.7) Nm
McGarvey et al. ²⁸	• Dom: 49.2 (20.0) Nm • Ndom: 48.0 (18.9) Nm	• Dom: 31.4 (11.9) Nm • Ndom: 29.8 (11.8) Nm	• Dom: 5.5 (2.4) Nm • Ndom: 5.1 (2.3) Nm	• Dom: 6.1 (2.5) Nm • Ndom: 5.5 (2.2) Nm
Nogueira et al. ²⁹	Ndom: 58.8 (6.8) Nm			
Rey et al. ¹⁷			Dom: • Male: 7.0 Nm • Female: 4.5 Nm Ndom: • Male: 5.9 Nm • Female: 3.9 Nm	Dom: • Male: 11.5 Nm • Female: 7.6 Nm Ndom: • Male: 9.8 Nm • Female: 6.9 Nm
Timm et al. ³⁰			Cylinder handle: • Pronation: 5.9 (2.4) Nm Screwdriver handle: • Pronation: 5.7 (2.4) Nm Doorknob handle: • Pronation: 7.7 (2.4) Nm	Cylinder handle: • Supination: 6.6 (2.3) Nm Screwdriver handle: • Supination: 7.3 (2.5) Nm Doorknob handle: • Supination: 9.9 (3.1) Nm
Viitasalo et al. (^a 2) ³¹	92.4 (13.2) Nm			
Wong and Moskovitz ³²			BHD (kg): 42.9 (15.2) Nm Cybex: 5.4 (2.8) Nm	BHD (kg): 40.7 (17.9) Nm Cybex: 5.0 (2.3) Nm
Yang et al. ³³	• 56°: 31.4 (16.0) Nm • 70°: 29.9 (14.4) Nm • 84°: 28.2 (14.2) Nm	• 56°: 23.9 (9.4) Nm • 70°: 24.1 (8.3) Nm • 84°: 27.5 (9.2) Nm		

*2 Results derived from graphs. Dom, dominant; Ndom, nondominant. Manufacturer details: Ametek Accuforce II (Ametek, Largo FL), Chatillon DFG 100 (John Chatillon and Sons, Greensboro, NC), BTE work simulator (Baltimore Therapeutic Equipment Co., Baltimore, MD), Cybex dynamometer (Cybex, Division of Lumex Inc., Ronkonkoma, NY), BHD (Fabrication Enterprises Inc., White Plains, NY), Cybex 6000 (Cybex International, Inc., Medway, MA)

in the review, although they did differ from each other regarding the device used to measure the strength, the study populations, and the positions in which the subjects were tested. These studies were used to determine normative values of the isometric elbow strength.

These normative values should be interpreted with caution because different measurement devices were used. Even though Vermeulen et al.⁹ found that both fixed and hand-held dynamometers are reliable for strength measurements, differences were found between the results of the elbow strength measurements using these types of dynamometers. A possibility for these differences could be that some of these dynamometers were not commercially available and therefore it could be difficult to reproduce the results. Using commercially available dynamometers to measure the isometric elbow strength is easier for other researchers with respect to reproducing the results found in other studies.

It should be noted that, next to different measurement devices, different positions of the subjects were

also used. This could also have influenced the normative values and is therefore another reason for interpreting the normative values with caution. For flexion and extension measurements, most studies have evaluated their subjects when they were seated with their shoulder in a neutral position, the elbow in 90° in flexion and the forearm supinated. Because only the elbow flexion–extension strength should be measured, subjects need to keep their shoulder in neutral; otherwise, shoulder muscles could influence the strength.¹⁰ Several studies have reported that the maximum flexion–extension elbow strength occurs at 90° flexion of the elbow.^{11,12} The biceps moment arm has a larger peak when the forearm is in a supinated position¹³ and most studies included in the present review used the forearm in supinated position. It is therefore a logical position to use to produce the most valid and reproducible results for the flexion–extension strength of the elbow. This position of the subject is not the best position for measuring the pronation–supination strength of the forearm. Of the nine studies included in the present review that

Table 3. Mean (SD) of the strength/torque (Nm) weighed by the amount of subjects included in the different studies with the ratio between the dominance of the arms.

Movement	Dominance of the arm	Sex	Strength mean (SD)	Ratio dominance (D : ND)
Flexion	Dominant	Male	76.7 (15.0)	1 : 0.94
		Female	52.5 (18.3)	
	Nondominant	Male	65.6 (5.6)	
		Female	55.6 (14.3)	
Extension	Dominant	Male	48.2 (5.6)	1 : 0.97
		Female	40.2 (13.3)	
	Nondominant	Male	46.9 (5.9)	
		Female	39.1 (13.3)	
Pronation	Dominant	Male	10.0 (7.8)	1 : 0.93
		Female	6.4 (7.1)	
	Nondominant	Male	10.0 (8.5)	
		Female	5.9 (7.7)	
Supination	Dominant	Male	10.7 (7.1)	1 : 0.94
		Female	7.1 (6.7)	
	Nondominant	Male	10.2 (7.7)	
		Female	6.6 (7.1)	

evaluated the pronation–supination strength, most subjects were seated with their shoulders in neutral position and the elbow in 90° flexion with a neutral forearm position. Most studies evaluated this strength with the shoulder in a neutral position for the same reason as that with respect to flexion–extension. Studies have shown that the maximum strength of pronation–supination can be achieved when the elbow is in a 45° or 90° flexion.^{14,15} Because most studies used the neutral forearm position, it is the most logical position for pronation–supination strength measurement and easier to compare with other studies. Therefore, the most logical positions for further research into the elbow strength for flexion–extension are with the subjects seated, neutral shoulder position, 90° elbow flexion and their forearm supinated, whereas, for pronation–supination, the subjects are seated and have a neutral shoulder position, with either the elbow in 45° or 90° flexion and their forearm in a neutral position.

The literature describes differences in strength between men and women.^{8,16,17} This was also found when evaluating the strength per movement. Significant differences were found between men and

women ($p < 0.011$), except for the elbow flexion ($p = 0.097$). Evaluating the differences between the dominant and the nondominant arm, no significant differences were observed ($p = 0.312$). This was not in accordance with other literature, which found a significant difference with respect to dominance of the arm.^{8,16} However, the ratios between the dominant and the nondominant arm did show that the nondominant arm was slightly weaker than the dominant arm. Another observation was the large SDs of some of the normative values. These deviations were a result of a large range of elbow strengths found in the studies included in the present review. Therefore, the normative values and ratios have to be considered with caution.

To use normative results with more certainty, additional research is required. For future research, it is recommended that the moment arms of the flexion–extension and the pronation–supination movements should be measured in addition to the absolute force to be able to convert results to different measurement units (e.g. moments) and therefore be comparable with the other study results. Research has to be carried out

with a commercially available dynamometer for easy reproducibility (preferably not a hand-held dynamometer but, instead, a static, portable dynamometer). The measurements should be executed in the positions that were mentioned previously: the subject seated with their shoulder in neutral position and their elbow flexed in 90° and, for flexion–extension strength, the forearm in supinated position, whereas, for pronation–supination strength, the forearm should be placed in a neutral position. Using these positions and a dynamometer in a large scaled study with a diverse study population, it will be possible to produce normative values that are representative of the population and can also be used with certainty.

Conclusions

This systematic review provided normative values of the isometric flexion and extension movement of the elbow and the pronation and supination movement of the forearm. Even though the studies of which the normative values are extracted from differ from each other a lot, the normative values can still be used as an indication of the isometric elbow strength. The normative values were also used to determine a strength ratio between the dominant and the nondominant arm, which demonstrated that the nondominant arm is slightly weaker than the dominant arm. This ratio can also be used to give an indication of the elbow strength when compared to the contralateral limb of patients. To obtain the most reproducible and comparable results, the flexion–extension strength of the elbow should be measured with the patient in a seated position, with a neutral shoulder position, the elbow in 90° flexion and the forearm in supination. For measuring pronation–supination strength, the patient has to be in the same position, except for the elbow, which can be in 45° or 90° flexion, and the forearm should be in neutral position.

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Supplementary material

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References

1. Sardelli M, Tashjian RZ and MacWilliams BA. Functional elbow range of motion for contemporary tasks. *J Bone Joint Surg Am* 2011; 93: 471–477.
2. Aizawa J, Masuda T, Koyama T, et al. Three-dimensional motion of the upper extremity joints during various activities of daily living. *J Biomech* 2010; 43: 2915–2922.
3. Gates DH, Walters LS, Cowley J, et al. Range of motion requirements for upper-limb activities of daily living. *Am J Occup Ther* 2015; 70: 7001350010p1–7001350010p10.
4. Nesterenko S, Domire ZJ, Morrey BF, et al. Elbow strength and endurance in patients with a ruptured distal biceps tendon. *J Shoulder Elbow Surg* 2010; 19: 184–189.
5. Ploegmakers JJW, The B, Bratty M, et al. The effect of a Galeazzi fracture on the strength of pronation and supination two years after surgical treatment. *Bone Joint J* 2013; 95B: 1508–1513.
6. Wretenberg P, Ericson A and Stark A. Radial head prosthesis after fracture of radial head with associated elbow instability. *Arch Orthop Trauma Surg* 2006; 126: 145–149.
7. Günel I, Köse N, Erdogan O, et al. Normal range of motion of the joints of the upper extremity in male subjects, with special reference to side. *J Bone Joint Surg Am* 1996; 78: 1401–1404.
8. Askew LJ, An KN, Morrey BF, et al. Isometric elbow strength in normal individuals. *Clin Orthop Relat Res* 1987; 261–266.
9. Vermeulen HM, de Bock GH, van Houwelingen HC, et al. A comparison of two portable dynamometers in the assessment of shoulder and elbow strength. *Physiotherapy* 2005; 91: 101–112.
10. Bohannon RW. Shoulder position influences elbow extension force in healthy individuals. *J Orthop Sports Phys Ther* 1990; 12: 111–114.
11. Guenzkofer F, Engstler F, Bubb H, et al. Isometric elbow flexion and extension joint torque measurements considering biomechanical aspects. *Proc First Int Symp Digit Hum Model*. https://www.researchgate.net/profile/Fabian_Guenzkofer2/publication/228535401_Isometric_elbow_flexion_and_extension_joint_torque_measurements_considering_biomechanical_aspects/links/09e4150643c5e54fba000000.pdf.
12. Singh M and Karpovich PV. Strength of forearm flexors and extensors in men and women. *J Appl Physiol* 1968; 25: 177–180.
13. Murray WM, Delp SL and Buchanan TS. Variation of muscle moment arms with elbow and forearm position. *J Biomech* 1995; 28: 513–525.
14. O'Sullivan LW and Gallwey TJ. Upper-limb surface electro-myography at maximum supination and pronation torques: the effect of elbow and forearm angle. *J Electromyogr Kinesiol* 2002; 12: 275–285.
15. Shaaban H, Pereira C, Williams R, et al. The effect of elbow position on the range of supination and pronation of the forearm. *J Hand Surg Eur Vol* 2008; 33: 3–8.
16. Matsuoka J, Berger RA, Berglund LJ, et al. An analysis of symmetry of torque strength of the forearm under

- resisted forearm rotation in normal subjects. *J Hand Surg Am* 2006; 31: 801–805.
17. Rey P-B, Jardin E, Uhring J, et al. [Is there any correlation between the strength of pronation and supination of the dominant hand and that of the non-dominant one in right-handed healthy adults: preliminary results]. *Chir Main* 2014; 33: 17–22.
18. Andrews AW, Thomas MW and Bohannon RW. Normative values for isometric muscle force measurements obtained with hand-held dynamometers. *Phys Ther* 1996; 76: 248–259.
19. Balogun JA and Onigbinde AT. Hand and leg dominance: do they really affect limb muscle strength?. *Physiother Theory Pract* 1992; 8: 89–96.
20. Bohannon RW. Comparability of force measurements obtained with different strain gauge hand-held dynamometers. *J Orthop Sports Phys Ther* 1993; 18: 564–567.
21. Bohannon R and Saunders N. Hand-held dynamometry: a single trial may be adequate for measuring muscle strength in healthy individuals. *Physiother Canada* 1990; 42: 6–9.
22. Coombes BK, Bisset L and Vicenzino B. Elbow flexor and extensor muscle weakness in lateral epicondylalgia. *Br J Sports Med* 2012; 46: 449–453.
23. Darcus HD. The maximum torques developed in pronation and supination of the right hand. *J Anat* 1951; 85: 55–67.
24. Douma RK, Soer R, Krijnen WP, et al. Reference values for isometric muscle force among workers for the Netherlands: a comparison of reference values. *BMC Sports Sci Med Rehabil* 2014; 6: 10.
25. Harbo T, Brincks J and Andersen H. Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *Eur J Appl Physiol* 2012; 112: 267–275.
26. Herzberg G, Berthonnaud E, Bestion A, et al. [Testing of pronation and supination strength in the outpatient setting: a preliminary study]. *Chir Main* 2007; 26: 40–43.
27. Kramer JF, Nusca D, Bisbee L, et al. Forearm pronation and supination: reliability of absolute torques and non-dominant/dominant ratios. *J Hand Ther* 1994; 7: 15–20.
28. McGarvey SR, Morrey BF, Askew LJ, et al. Reliability of isometric strength testing. Temporal factors and strength variation. *Clin Orthop Relat Res* 1984; 301–305.
29. Nogueira F, Libardi C, Vechin F, et al. Comparison of maximal muscle strength of elbow flexors and knee extensors between younger and older men with the same level of daily activity. *Clin Interv Aging* 2013; 8: 401–407.
30. Timm WN, O'Driscoll SW, Johnson ME, et al. Functional comparison of pronation and supination strengths. *J Hand Ther* 1993; 6: 190–193.
31. Viitasalo JT, Era P, Leskinen A-L, et al. Muscular strength profiles and anthropometry in random samples of men aged 31–35, 51–55 and 71–75 years. *Ergonomics* 1985; 28: 1563–1574.
32. Wong CK and Moskovitz N. New assessment of forearm strength: reliability and validity. *Am J Occup Ther* 2010; 64: 809–813.
33. Yang J, Lee J, Lee B, et al. The effects of elbow joint angle changes on elbow flexor and extensor muscle strength and activation. *J Phys Ther Sci* 2014; 26: 1079–1082.
34. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement. *Open Med* 2009; 3: 123–130.