Design of a protocol for measuring pronation and supination strength of the forearm in different postures

ABSTRACT

Background: Pronosupination strength can be affected by different pathologies, limiting the performance of many daily activities. For a complete functional evaluation of those pathologies, an analysis of pronation and supination forces should be included. Although there are some assessment methodologies, there exists a disparity both in the measurement protocols and in the results regarding the influence of sex, age, upper limb dominance or forearm posture on strength. **Objectives**: We have designed a device and a standardized protocol for measuring pronation and supination torques in different positions of the forearm, and have studied its reliability as well as the influence of sex, age and upper limb dominance on the forces. **Method:** The pronation and supination strength of 39 healthy subjects was studied in 5 forearm positions: 30˚ and 60˚ of supination, neutral rotation, 30˚ and 60˚ of pronation. The influence of sex, age and upper limb dominance was studied using repeated-measurements ANOVA. Intrarrater and interrater reliability was studied in 17 of those subjects by obtaining the Intraclass Correlation coefficients (ICCs) from three measurement sessions. **Results:** Except for pronation exerted at 60º of pronation, all ICCs ranged from 0.72 to 0.97. Sex, dominance and posture significantly affected pronosupination strength ($p<0.05$), with the highest supination strength found at 60º of pronation and the highest pronation strength at 60º of supination. **Conclusions:** a reliable pronosupination torque assessment device and standardized measurement protocol have been developed. To consider its use in the clinical setting, the influence of sex, dominance and forearm posture must be considered.

KEYWORKDS: pronation, supination, torque, reliability, forearm, isometric contraction, age factor, sex factor, posture.

INTRODUCTION

Pronosupination, or rotation of the forearm around its longitudinal axis, provides an extra degree of freedom to the wrist, which in turn allows the hand to be oriented at any angle. Although the maximum arc of pronosupination oscillates approximately between 71° of pronation and 81° of supination, most activities are carried out with at functional range of about 100°, between 50° of pronation and 50° of supination (Kapandji A. 2001).

In addition to a preserved range of motion, the exertion of rotational strength in various positions or angles of rotation of the forearm is required in common activities such as using a screwdriver, turning a knob or activating a lever. Many ligamentous (Hwang et al. 2018), osteological (Melamed et al. 2015) or musculotendinous pathologies (Inagaki 2013, Citak et al. 2011) may affect pronosupination strengths, interfering in the execution of those activities. A deep knowledge not only of the kinematics, but also of the stability and strengths acting at the elbow, will be paramount for a proper monitoring, design and treatment selection (Inagaki 2013, Lees 2016).

A complete evaluation of the elbow should ideally include the measurement of pronosupination strengths exerted in different functional postures of the forearm, which involve diverse configurations of the radius, ulna and carpal structures, and therefore changes in the lever arm, the stability of structures, and in the transmission of strengths, which seems to be maximal at 60˚ of supination of the forearm (Lees 2016). Moreover, a comprehensive assessment of the different functional positions of the forearm is more representative of the diverse functional requirements of everyday activities. Besides, the degree of elbow flexion influences the range of forearm pronation and supination: greatest pronation is achieved when the elbow is fully extended, whereas a greater supination is achieved with full flexion (Lees 2016). The degree of elbow flexion also influences strength, being 90˚ of flexion the position where biceps brachii has the maximal impact on supination and therefore the most advantageous for this strength (Güleçyüz et al. 2017). Hence, it seems appropriate to consider an intermediate level of elbow flexion (90˚) as the ideal posture to assess the pronosupination range of motion and isometric (Kapandji A. 2007). Yet authors often measure pronosupination strength at 90˚ and also at 45º of elbow flexion (Kotte et al. 2018).

There are not many studies that have assessed both pronation and supination strengths in vivo considering different rotation postures of the forearm (Ploegmakers et al. 2015, Ellenbecker 2006, Gordon et al. 2004, Matsuoka et al. 2006). Of those, very few do it in 90º of elbow flexion (Gordon et al. 2004), and no one has analyzed the influence of relevant factors over strength, including sex, age, upper limb dominance (Kotte et al. 2018) and the correlation between those factors in the same study.

In this study, we propose a new protocol for measuring pronosupination strength, with the elbow flexed at 90º, at 5 different functional postures of the forearm (within a range of 120º of forearm rotation). Additionally, we studied the influence of, sex, upper limb dominance, age and forearm posture over pronosupination strength. Our ultimate goal is to validate a measurement protocol that has been designed in order to be applicable in clinical environments, considering aspects of the person that can influence the results.

MATERIAL AND METHODS

We used a static, square-headed torque load weighing sensor with a sensitivity of >0.01Nm and a range of ±10Nm to measure the rotational torque strength. A least squares regression was performed in order to assure the adjustment of the sensor (Kullaa, 2010). An external framework was designed (see Figure 1. Handle of the measuring device, with), including a cylindric grip handle whose orientation could be adjusted to 60º of supination (60SUP), 30º of supination (30SUP), 0º of pronosupination (NEU), 30º of pronation (30PRO) and 60º of pronation (60PRO) of the forearm. This allowed us to measure the torque (Nm) in each posture during isometric pronation and supination.

Figure 1. Handle of the measuring device, with marks for 60º (60SUP and 60PRO), 30º (30SUP and 30PRO) and 0º (NEU) postures represented by numbers 1 to 5.

A sample of 39 healthy men and women between 18 and 65 years old participated in the study. The main exclusion criterion was the presence of any discomfort or pathology in the upper limbs that could affect the measurements.

Measurements were performed with the subjects in sitting posture, elbow flexed at 90˚ and relaxed shoulder. A foam pad was placed under the arm to prevent compensatory shoulder rotations. Both the dominant (D) and non-dominant (ND) upper limb were assessed, always starting with the dominant side. The subjects were requested to exert as much force as they could in each posture, during 2 to 3 seconds, in the following order:

1. Isometric pronation (Pro) at postures: 60SUP, 30SUP, NEU, 30PRO and 60PRO.

2. Isometric supination (Sup) at postures: 60PRO, 30PRO, NEU, 30SUP and 60SUP.

The evaluators made sure that the subjects had understood the instructions correctly, letting them practice before the measurements, without exerting the maximum force.

The inter-rater and intra-rater reliability of the system and the protocol was evaluated with a subsample of 17 subjects. Two physiotherapists trained in the procedure (A and B) participated as evaluators. During the first session, carried out in a single day, each evaluator performed the whole measurement, with a resting period of five minutes in between to avoid muscle fatigue. To reduce a potential bias in the inter-rater reliability study, during the first session, the first and second evaluator (A or B) were chosen randomly for each subject. In an interval greater than 24 hours and less than a week, evaluator A re-assessed each subject. All measurements were done following the previously described protocol, but in the second (inter-rater) and third (intra-rater) measurements, only the dominant limb was assessed.

Sex, age and upper limb dominance of the subjects were recorded as independent variables. Subjects were classified into 4 age groups: A0 (18 to 29 years old), A1 (30 to 39 years old), A2 (40 to 49 years old), and A3 (50 to 65 years old).

Strengths were characterized as the maximum supination and pronation torques (Nm), for each forearm posture and side (dominant and non-dominant), so that 10 values per limb were recorded (20 per subject): Pro_SUP60, Pro_SUP30, Pro_NEU, Pro_PRO30, Pro_PRO60, Sup_PRO60, Sup_PRO30, Sup_NEU, Sup_SUP30 and Sup_SUP60, where the first three characters represent the type of isometric strength recorded (Pro=pronation strength; Sup=supination strength), and the rest correspond to the orientation of the forearm as previously described.

Strengths for each direction, posture and side were described by their means and standard deviations. We used the Intraclass Correlation Coefficient ICC (2,1) to measure inter-rater and intra-rater reliability of strengths for the dominant side (Gisev et al.2013, Shrout & Fleiss 1979). The standard error of measurement (SEM), was calculated as a further measure of reliability. SEM values were expressed as percentages of the mean score, which were considered acceptable when <20% (Barbado et al. 2020).

The influence of the subjects' characteristics and of forearm posture on measured strengths was analyzed by a repeated-measurements ANOVA, using a mixed linear model with sex, age, dominance of upper limb and posture of the forearm as fixed factors, and the subject as random effect. The relevant interactions between fixed factors were selected by a stepwise algorithm (Venables & Ripley 2002), and analyzed by a simple effects test (Schabenberger et al. 2000).

Statistically significant differences were defined considering a Type-I error of $\alpha=0.05$ ($p<0.05$). All the analysis was done with the "RStudio" package 2021.09.1.372 for statistical computing (R. Core Team 2014).

The study was approved by the University Ethics Committee in Human Research. All subjects agreed to participate after being informed of the purposes and methodology of the research, and signed an informed consent.

RESULTS

The whole sample of subjects and the subsample that participated in the reliability study was evenly distributed by sex and age (see Table 1). All subjects were right handed except for one, who did not take part in the reliability study.

Table 1. Characteristics of the subject samples. Age groups A0, A1, A2, and A3 as defined in the main text. The sizes of the subsample used in the reliability study is given in parentheses.

Age / Sex	A0	A1	A2	A3	TOTAL
Men	3 (2)	5 (4)	5 (2)	7 (2)	20 (10)
Women	4 (2)	5 (2)	6 (2)	4 (1)	19 (7)
TOTAL	7 (4)	10 (6)	11 (4)	11 (3)	39 (17)

Inter-rater and inter-rater reliability

Intraclass correlation coefficients obtained for test-retest and inter-rater reliability and standard error of measurement can be seen in Table 2. In all cases except pronation strength at 60º of pronation (Pro_60PRO), ICC was greater than 0.70 and SEM smaller than 20%.

Table 2. Intra-rater and inter-rater ICC(2,1) and SEM for strengths at different postures of the dominant limb.

	INTRA-RATER		**INTER-RATER**	
	ICC	**SEM%**	**ICC**	**SEM%**
Pro_60SUP	0.916	10.30	0.803	13.84
Pro_30SUP	0.942	7.84	0.921	8.00
Pro_NEU	0.809	14.26	0.890	9.64
Pro_30PRO	0.728	17.81	0.788	13.74
Pro_60PRO	0.573	36.36	0.753	25.40
Sup_60SUP	0.893	8.50	0.795	13.74
Sup_30SUP	0.918	8.09	0.881	9.22
Sup_NEU	0.911	9.07	0.907	9.39
Sup_30PRO	0.948	7.01	0.906	9.97
Sup_60PRO	0.973	5.77	0.942	8.30

Influence of subject's characteristics on strength

The stepwise selection algorithm left the four main factors (sex, age, dominance and forearm posture) and the interaction between dominance and age as influential factors of the statistical model. The ANOVA showed a significant effect of sex, dominance and posture of the forearm on strength (see Table 3).

Table 3. Results of the ANOVA test (Type II).

Variable	**F value**	**P-value**
Posture ($F_{9,728}$)	159.68	**0.000**

Sex ($F_{1,34}$)	91.71	**0.000**
Dominance ($F_{1,728}$)	7.09	**0.008**
Age ($F_{3,34}$)	2.07	0.102
Dominance-age ($F_{3,728}$)	3.61	**0.008**

Although age itself did not have a significant effect on strength, we found a significant interaction between this factor and dominance, specifically for group A1 as seen on the post hoc analysis (see Table 4 with specific strength values).

Table 4. Average strength and Standard Deviation (SD) for Dominant and non-dominant upper limb in each age group. F value corresponds to post-hoc analysis of the interaction between dominance and age for each given group.

	NON DOMINANT		**DOMINANT**			
Age group	**Mean (Nm)**	**SD (Nm)**	**Mean (Nm)**	**SD (Nm)**	**F value**	**P-value**
A0	3.97	2.073	4.22	2.373	1.88	0.514
A1	4.52	2.274	5.15	2.696	15.90	**0.000**
A2	5.29	2.715	5.26	2.556	0.04	1.000
A3	5.20	2.554	5.25	2.603	0.10	1.000

The greatest supination force was achieved in 60PRO, and the greatest pronation force in 60SUP (see Figure 2). In the post-hoc test it was found that those two forces were greater than those made in the rest of the postures for Supination and Pronation respectively (p=0.000).

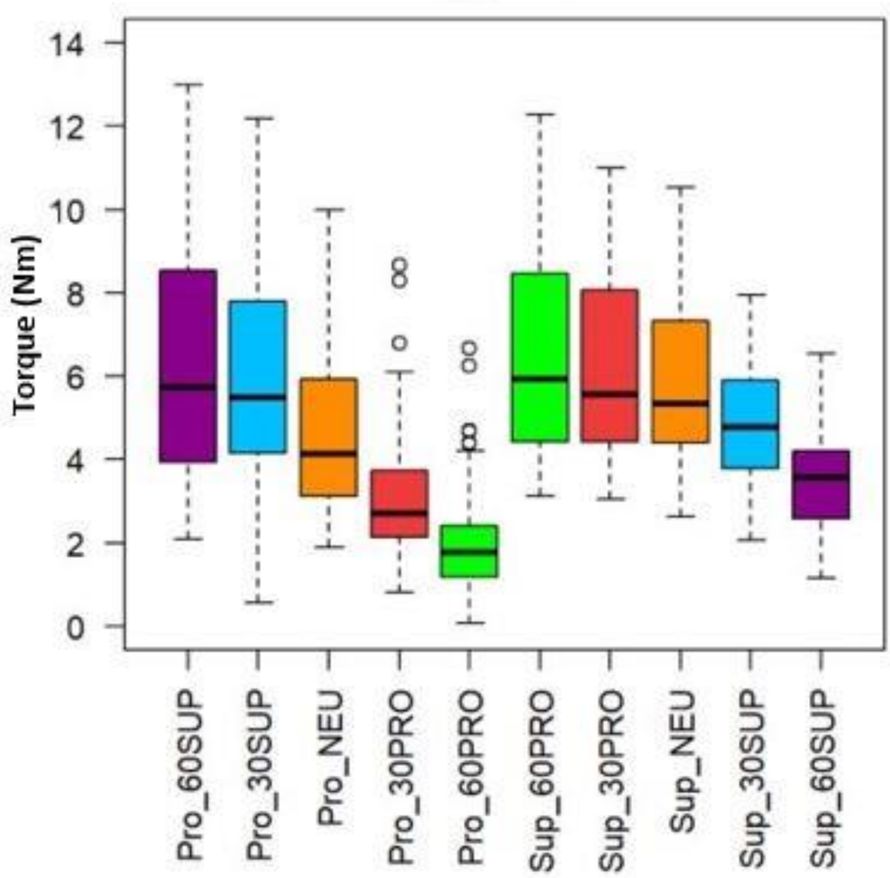

Figure 2. Distributions of pronation (Pro) and supination (Sup) strengths at each posture of the forearm (n=39).

DISCUSSION

Although the gold standard for the measurement of strength is isokinetic dynamometry (Pienimäki et al. 2002, Ellenbecker 2006), those systems are generally complex and overall unfit for routine clinical practice (Wong & Moskovitz 2010). Alternatively, there are simpler devices such as the Baseline dynamometer (Fabrication Enterprises Inc., White Plains, NY, USA), which allows to record isometric strength at one or various rotation postures (Axelsson et al. 2020, (Kerschbaum et al. 2017, Ploegmakers et al. 2015). Even if the results of validity and reliability of the latter are good, studies with them are scarce (Wong & Moskovitz 2010, Axelsson & Kärrholm 2018), and there is no consensus regarding which specific protocol and posture of the upper limb are optimal for measuring with such system.

Some researchers have developed non-commercial devices for measuring pronosupination isometric strength, with different protocols and dissimilar findings (Matsuoka et al. 2006, Güleçyüz et al.2017, Gordon et al. 2004). In line with those authors, we have also developed our own device. Additionally, we have defined a standardized protocol that may be useful in a clinical context to evaluate the isometric pronation and supination strength, considering different functional rotation angles of the forearm and with 90˚ of elbow flexion, which is considered the most appropriate posture (Kapandji A. 2007). We have verified the reliability of both the device and the protocol and studied the influence of different factors over strength in the same study. To do so, we studied a sample of 39 healthy people (17 in the reliability study) that was comparable or greater than those of previous studies that used by authors like Ellenbecker 2006, Wong & Moskovitz 2010 , or Gordon et al., 2004.

The results of our study confirm that the relative reliability of the device and protocol is either good or excellent, with most of the ICCs ranging from 0.72 to 0.97(Koo & Li 2016). Overall, test-retest intra-rater reliability seems to be higher than inter-rater, with most of the ICCs above 0.9 (excellent agreement). This seems logical, since in interrater reliability factors related to the experience and capabilities of each evaluator come into play (Tuijn et al. 2012). The ICCs found are either equivalent or higher to the correlation coefficients found by

Kramer et al. 1994 for forearm rotation torques measured with BTE (WS20) and the Cybex (340) dynamometers (ICCs ≥0.75). Our results are also similar to those found by authors like Axelsson & Kärrholm 2018 or Wong & Moskovitz 2010, with ICCs ranging from 0.88 to 0.96 for pronation and supination torques, and between 0.85 and 0.97 for inter-rater and intra-rater reliability respectively. These ICCs seem to be a bit higher than ours, but we should take into consideration a few relevant methodological differences that may justify this:

- Both studies considered only strength for neutral rotation of the forearm, while ours analyzes reliability at six different postures. The ICCs that we obtained for neutral (NEU) posture were also above 0.8 in our study.
- Previous authors analyzed the reliability of the devices under study, while we also studied the reliability of the measurement protocol. Given that we tried to keep this protocol as short as possible to maximize its clinical usability, we only obtained one value for each position, while they used either the peak or the mean value out of three trials
- There were also other differences in the protocol, like the elbow flexion (45˚) or the handle shape (doorknob) (Wong & Moskovitz 2010).

We have obtained SEM values lower than 20%, which confirms that the test provides reliable parameters (Barbado et al. 2020). Only Pro_PRO60 obtained a lower intra-rater ICC (0.57) and a SEM over 20%, coinciding with the lowest strength found and the posture referred to as the most difficult one by the participants. This posture produces discomfort (Mukhopadhyay et al. 2007), which might relate to the increased variability, and it is disadvantageous from an anatomical point of view, with little to none lever arm when it comes to exerting pronation force (Kapandji A. 2001).

Regarding normative strength values and the effect of different intrinsic factors over those, there are discrepancies in the available studies. There is no consensus on the protocols to determine those values, which should be interpreted with caution (Kotte et al. 2018). What does seem clear though, is that sex significantly affects pronosupination strength (Kerschbaum et al. 2017), being higher in men, which has also been confirmed in our study.

Concerning dominance, while some authors find a clear effect (Gallagher et al. 1997), others only find it for either pronation or supination (Ellenbecker 2006, Ploegmakers et al. 2015), or only in part of the population under study (Kerschbaum et al. 2017, Güleçyüz et al. 2017). In our study, we have found a statistically significant difference for dominance.

Regarding age, there are few reported data in the literature. In our study, we found no effect of age over strength. However, a statistically significant interaction between dominance and age has been found, occurring mainly in group A1 (30 to 39) years, and decreasing at older ages. This could be related to higher peak forces reached by people under 39, which led to a bigger difference between the dominant and non-dominant side (Güleçyüz et al. 2017)

We also found that the forearm posture significantly affected the results, and that both pronation and supination strengths were greater when exerted against the adopted posture. Regarding pronation, the greatest force is generated at 60º of supination. This aligns with the results of Matsuoka et al. 2006, Gordon et al. 2004 and O’Sullivan & Gallwey 2002, who also found greater pronation forces around mid-supination of the forearm. Unlike the latter, we did not find that pronation forces were clearly greater than those of supination at 60º in the opposite posture. In contrast to our findings, Haugstvedt et al. 2001 found greater generation of forces by pronator quadratus and pronator teres between the neutral posture and 30º of supination of the forearm; we think that those differences are justified by the absence of grip in their study (eliminating the effect of the carpal muscles), and by the fact that it was performed invitro, ignoring the agonist-antagonistic actions of the in-vivo movement. Supination strength was highest at 60º pronation in our study. This coincides with the findings of Gordon et al. 2004. In the study of Haugstvedt et al. 2001 it was also found that the biceps, the most powerful counter-resistance supinator, generates up to 4 times more torque between 10º and 30º of forearm pronation compared to other postures. We think that in our study the greatest forces were found at 60º, and not at 30º or in neutral posture like in previous studies (O'Sullivan & Gallwey 2002), due to the added action of the carpal musculature that involves our type of grip (Gordon et al. 2004). These muscles, mainly extensor and flexor carpi radialis, would have relevant involvement in postures of maximum rotation of the forearm (Haugstvedt et al. 2001)

Lastly, we would like to add some methodological considerations regarding our study:

- Some authors (Gordon et al. 2004) considered that to evaluate solely the action of the pronating and supinating musculature of the forearm, the added movement of the wrist should be blocked by using a wrist clamp, ruling out any added grip force. Our intention was to replicate a real-life functional movement, where the hand also participates by grabbing the object. Therefore, we have used a cylindrical grip, which means involvement of carpal musculature with a complementary action on pronosupination.

- Our goal is that the designed protocol could be replicated in the clinical setting, and thus we tried to avoid making it unnecessarily lengthy. With the aim of checking the reliability of the protocol, and not only that of the device, a single repetition was made for each force and posture, following the same standardized order of postures. This could have negatively affected the results of our reliability study.
- Only one person in our sample was left-handed. Therefore, we cannot assure that the effect of dominance found is equivalent in these subjects.

Conclusions

- *The device developed, through the proposed protocol, allows to reliably measure pronation and supination strength of the forearm in different functional rotation angles.*
- *We found significant differences in the forces generated according to sex and dominance. These differences should be considered when establishing comparisons between subjects or between the dominant and non-dominant side.*
- *The posture of the forearm influences the ability to generate force, being greater in the opposite postures: supination force in pronation of 60º and pronation force in supination of 60º.*

Acknowledgements: Activity developed within the framework of the IBERUS project. Technological Network of Biomedical Engineering applied to degenerative pathologies of the neuromusculoskeletal system in clinical and outpatient settings (CER-20211003), CERVERA Network financed by the Ministry of Science and Innovation through the Center for Industrial Technological Development (CDTI), charged to the General State Budgets 2021 and the Recovery, Transformation and Resilience Plan.

Declaration of competing interest: None

REFERENCES

Axelsson, P., & Kärrholm, J. (2018). New Methods to Assess Forearm Torque and Lifting Strength: Reliability and Validity. *The Journal of Hand Surgery (American Ed.), 43*(9), 865.e1-865.e10. 10.1016/j.jhsa.2018.01.009

Axelsson, P., Sollerman, C., & Kärrholm, J. (2020). Validity and Responsiveness of Forearm Strength Measurements in the Evaluation of Distal Radioulnar Joint Implant Arthroplasty. *The Journal of Hand Surgery, 45*(8), 778.e1-778.e7. 10.1016/j.jhsa.2020.01.013

Barbado, D., Gomez-Illan, R., Moreno-Navarro, P., Valero-Conesa, G., Reina, R., & Vera-Garcia, F. J. (2020). Postural control quantification in minimally and moderately impaired persons with multiple sclerosis: The reliability of a posturographic test and its relationships with functional ability. *Journal of Sport and Health Science, 9*(6), 677-684.

Citak, M., Backhaus, M., Seybold, D., Suero, E. M., Schildhauer, T. A., & Roetman, B. (2011). Surgical repair of the distal biceps brachii tendon: a comparative study of three surgical fixation techniques. *Knee Surgery,* *Sports Traumatology, Arthroscopy, 19*(11), 1936-1941. 10.1007/s00167-011-1591-0

Ellenbecker, T. S. (2006). Isokinetic profile of wrist and forearm strength in elite female junior tennis players. *British Journal of Sports Medicine, 40*(5), 411-414. 10.1136/bjsm.2005.023358

Gallagher, M. A., Cuomo, F., Polonsky, L., Berliner, K., & Zuckerman, J. D. (1997). Effects of age, testing speed, and arm dominance on isokinetic strength of the elbow. *Journal of Shoulder and Elbow Surgery*, *6*(4), 340-346.

Gisev, N., Bell, J. S., & Chen, T. F. (2013). Interrater agreement and interrater reliability: key concepts, approaches, and applications. *Research in Social and Administrative Pharmacy, 9*(3), 330-338.

Gordon, K. D., Pardo, R. D., Johnson, J. A., King, G. J. W., & Miller, T. A. (2004). Electromyographic activity and strength during maximum isometric pronation and supination efforts in healthy adults. *Journal of Orthopaedic Research, 22*(1), 208-213. 10.1016/S0736-0266(03)00115-3

Güleçyüz, M. F., Pietschmann, M. F., Michalski, S., Eberhard, F. M., Crispin, A., Schröder, C., Mittermüller, M. J., & Müller, P. E. (2017). Reference Values of Flexion and Supination in the Elbow Joint of a Cohort without Shoulder Pathologies. *BioMed Research International, 2017*, 1-9. 10.1155/2017/1654796

Haugstvedt, J., Berger, R. A., & Berglund, L. J. (2001). A mechanical study of the moment-forces of the supinators and pronators of the forearm. *Acta Orthopaedica Scandinavica, 72*(6), 629-634. 10.1080/000164701317269076

Herzberg, G., Berthonnaud, E., Bestion, A., & Dimnet, J. (2007). Évaluation de la force de pronosupination à la consultation: étude préliminaire. *Chirurgie De La Main, 26*(1), 40-43. 10.1016/j.main.2007.02.002

Hwang, J., Shields, M. N., Berglund, L. J., Hooke, A. W., Fitzsimmons, J. S., & O'Driscoll, S. W. (2018). The role of the posterior bundle of the medial collateral ligament in posteromedial rotatory instability of the elbow. *The Bone & Joint Journal, 100-B*(8), 1060-1065. 10.1302/0301-620X.100B8.BJJ-2017-0652.R2

Inagaki, K. (2013). Current concepts of elbow-joint disorders and their treatment. *Journal of Orthopaedic Science, 18*(1), 1-7. 10.1007/s00776-012-0333-6

Kapandji, A. (2007). The Physiology of the Joints: Upper Limb v. 1, Lower Limp v. 2: Annotated Diagrams of the Mechanics of the Human Joints.

Kapandji, A. (2001). Biomechanics of pronation and supination of the forearm. *Hand Clinics, 17*(1), 111-22, vii.

Kerschbaum, M., Maziak, N., Böhm, E., & Scheibel, M. (2017). Elbow flexion and forearm supination strength in a healthy population. *Journal of Shoulder and Elbow Surgery, 26*(9), 1616-1619. 10.1016/j.jse.2017.05.031

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155-163.

Kotte, S. H. P., Viveen, J., Koenraadt, K. L. M., The, B., & Eygendaal, D. (2018). Normative values of isometric elbow strength in healthy adults: a systematic review. *Shoulder & Elbow, 10*(3), 207-215. 10.1177/1758573217748643

Kramer, J. F., Nusca, D., Bisbee, L., MacDermid, J., Kemp, D., & Boley, S. (1994). Forearm Pronation and Supination: Reliability of Absolute Torques and Nondorninant/Dorninant Ratios. *Journal of Hand Therapy, 7*(1), 15-20.

Kullaa, J. (2010). Sensor validation using minimum mean square error estimation. *Mechanical Systems and Signal Processing, 24*(5), 1444-1457.

Lees, V. (2016). The functional anatomy of forearm rotation. *Journal of Hand and Microsurgery, 01*(02), 92-99. 10.1007/s12593-009-0022-7

Matsuoka, J., Berger, R. A., Berglund, L. J., & An, K. (2006). An Analysis of Symmetry of Torque Strength of the Forearm Under Resisted Forearm Rotation in Normal Subjects. *The Journal of Hand Surgery, 31*(5), 801-805. 10.1016/j.jhsa.2006.02.019

Melamed, E., Danna, N., Debkowska, M., Karia, R., Liporace, F., & Capo, J. T. (2015). Complex proximal ulna fractures: outcomes of surgical treatment. *European Journal of Orthopaedic Surgery & Traumatology, 25*(5), 851-858. 10.1007/s00590-015-1628-z

Mukhopadhyay, P., O'Sullivan, L., & Gallwey, T. J. (2007). Estimating upper limb discomfort level due to intermittent isometric pronation torque with various combinations of elbow angles, forearm rotation angles, force and frequency with upper arm at 90° abduction. *International Journal of Industrial Ergonomics, 37*(4), 313-325. 10.1016/j.ergon.2006.11.007

O'Sullivan, L. W., & Gallwey, T. J. (2002). Upper-limb surface electro-myography at maximum supination and pronation torques: the effect of elbow and forearm angle. *Journal of Electromyography and Kinesiology, 12*(4), 275-285. 10.1016/S1050-6411(02)00014-7

Pienimäki, T. T., Siira, P. T., & Vanharanta, H. (2002). Chronic medial and lateral epicondylitis: A comparison of pain, disability, and function. *Archives of Physical Medicine and Rehabilitation, 83*(3), 317-321. 10.1053/apmr.2002.29620

Ploegmakers, J., The, B., Wang, A., Brutty, M., & Ackland, T. (2015). Supination and Pronation Strength Deficits Persist at 2-4 Years after Treatment of Distal Radius Fractures. *Hand Surgery, 20*(03), 430-434. 10.1142/S0218810415500355

Schabenberger, O., Gregoire, T. G., & Kong, F. (2000). Collections of simple effects and their relationship to main effects and interactions in factorials. *The American Statistician, 54*(3), 210-214.

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin, 86*(2), 420.

Team, R. C. (2014). A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2014. *Available Online: Www.R-Project.Org (Accessed on 14 Febuary 2019),*

Tuijn, S., Janssens, F., Robben, P., & van den Bergh, H. (2012). Reducing interrater variability and improving health care: a meta-analytical review. *Journal of Evaluation in Clinical Practice, 18*(4), 887-895. 10.1111/j.1365-2753.2011.01705.x

Venables, W. N., & Ripley, B. D. (2002). Random and mixed effects. *Modern applied statistics with S* (pp. 271-300). Springer.

Wong, C. K., & Moskovitz, N. (2010). New Assessment of Forearm Strength: Reliability and Validity. *American Journal of Occupational Therapy, 64*(5), 809-813. 10.5014/ajot.2010.09140