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Estimation of Maximum Shoulder and Elbow Joint Torques Based on Demographics and Anthropometrics

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Abstract— **Repetitive movements that involve a significant shift of the body's center of mass can lead to shoulder and elbow fatigue, which are linked to injury and musculoskeletal disorders if not addressed in time. Research has been conducted on the joint torque individuals can produce, a quantity that indicates the ability of the person to carry out such repetitive movements. Most of the studies surround gait analysis, rehabilitation, the assessment of athletic performance, and robotics. The aim of this study is to develop a model that estimates the maximum shoulder and elbow joint torque an individual can produce based on anthropometrics and demographics without taking a manual measurement with a force gauge (dynamometer). Nineteen subjects took part in the study which recorded maximum shoulder and elbow joint torques using a dynamometer. Sex, age, body composition parameters, and anthropometric data were recorded, and relevant parameters which significantly contributed to joint torque were identified using regression techniques. Of the parameters measured, body mass index and upper forearm volume predominantly contribute to maximum torque for shoulder and elbow joints; coefficient of determination values were between 0.6 and 0.7 for the independent variables and were significant for maximum shoulder joint torque *($P<0.001$)* and maximum elbow joint torque *($P<0.005$)* models. Two expressions illustrated the impact of the relevant independent variables on maximum shoulder joint torque and maximum elbow joint torque, using multiple linear regression. Coefficient of determination values for the models were between 0.6 and 0.7. The models developed enable joint torque estimation for individuals using measurements that are quick and easy to acquire, without the use of a dynamometer. This information is useful for those employing joint torque data in biomechanics in the areas of health, rehabilitation, ergonomics, occupational safety, and robotics.**

Clinical Relevance— **The rapid estimation of arm joint torque without the direct force measurement can help occupational safety with the prevention of injury and musculoskeletal disorders in several working scenarios.**

I. Introduction

Human joint torque is relevant to a wide variety of contexts, such as sports performance, health, ergonomics and robotics. For example, in robotics, human joint motion and torque were analyzed to replicate natural joint movements and to improve ergonomics for collaborative human-machine tasks in industry [1, 2]. Research shows there is a link between high rotational torques in baseball pitching and overuse injuries of the shoulder, and maximum joint torque of an individual affects the fatigue they experience when carrying out repetitive, mid-air manual tasks [3, 4]. This ergonomic issue is particularly important to monitor because it is crucial to productivity and safety, as it is linked to injury and musculoskeletal disorders if not addressed in time. Current state-of-the-art is comprised of a model for the estimation of maximum knee joint torque as a function of joint angular velocity developed by Yeadon et al. using a four parameter function [5], as well as tables of average joint torques with respect to various parameters, as discussed below.

Otis *et al.* explored the effects of direction on the shoulder joint torques of dominant and non-dominant arms [6]. Günzkofer *et al.* completed similar work to model elbow joint torques in various directions [7]. Provins and Salter showed that position, direction of movement, and grip affect the maximum elbow joint torque a person can produce [8]. The testing involved pushing against a dynamometer at various joint angles, hand positions (supination/pronation), with and without a handle (to test the influence of grip), and the maximum joint torque was recorded in flexion, starting with the lower arm horizontal. The same conditions (flexion, supination, with handle) that the maximum joint torque was reported by Provins and Salter are implemented in the present study since the aim of the present study is to model the maximum joint torque only. Forearm volume and muscle thickness have an effect on the maximum joint torque of an individual, and thus are included in this study [8, 9]. However, the methods employed to measure such parameters were time consuming (i.e., water tank for measuring forearm volume) [8] or required specialized equipment (i.e., MRI for muscle thickness) [9]. A compromised approach to simplify the process involved calculating forearm volume using a measuring tape, and a weighing scale that measures body composition parameters to obtain muscle percentage. It has been shown that there is a positive correlation between forearm volume and maximum torque [8]. Joint torque predictions have be made from muscle response data using electromyography (EMG)

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techniques with success, yet this input is not considered in this study as it, requires specialized equipment [10, 11].

This study aims to develop models for the prediction of maximum joint torque which can be used in sectors that utilize joint torque data [1, 2, 3, 4], and help reduce the frequency of injuries in clinical and industrial settings. Additionally, such models can significantly simplify and accelerate measurement processes and negate the need for specialized equipment. The existing research described above provided the ground for the variables chosen as inputs for the estimation models, with a preference for easily and quickly measured parameters. It was hypothesized that height, BMI and forearm volume have the greatest influence on joint torque.

II. Methodology

Demographic and anthropometric data of 19 participants were recorded (Table I). All subjects were without injuries (self-reported) and in good physical condition. The clinically validated OMRON BF511 Body Composition Monitor [12] was used to measure the body's composition parameters, and a measuring tape to measure the forearm girth of the dominant arm (self-reported). Three measurements of forearm circumference were taken while the arm was in supination – the first measurement (forearm girth 1, Table I) was the girth at the olecranon, and the second (2) and third (3) measurements were 7*cm* distally from the previous measurement. Forearm volume can be found with these measurements by treating the segment as a truncated cone and has shown high correlation to the reliable and more time-consuming water tank method in a small sample [13].

TABLE I. Subjects information

Demographic and anthropometric data	
Participants (No)	19
Age (years)	37 ± 10
Sex (males/females)	10 Males, 9 Females
Dominant Hand (right/left)	16 Right-Handed, 3 Left-Handed
Height (m)	1.73 ± 0.08
BMI (kg/m²)	25.2 ± 3.8
Muscle %	31.9 ± 6.4
Fat %	29.1 ± 10.5
Forearm girth 1, 2, 3 (cm)	26.4 ± 2.4; 25.8 ± 3.0; 20.8 ± 3.4

Two seated testing positions were selected. The maximum force produced at the shoulder joint was tested with the arm outstretched straight ahead in supination with the shoulder, wrist and elbow joints in alignment (Fig. 1). The maximum force produced at the elbow joint was tested with the elbow joint flexed 90° relative to the upper arm on the coronal plane, and the palm in supination (Fig. 2).

Participants were seated to minimize the influence of the lower body on the measurements, similar to Provins and Salter; the thighs were horizontal, the feet rested on a footrest

Figure 1. Shoulder testing position.

Figure 2. Elbow testing position.

attached to the adjustable seat, and the back was upright [8]. The participant assumed a seated position that allowed the handle of a Walfront NK-500 push/pull dynamometer to touch their palm during testing. The PLA handle and clamp for the dynamometer were custom designed and 3D printed using a fused filament modelling printer. The settings of the dynamometer were adjusted to record the peak force produced. The participants were asked to perform a maximal voluntary contraction as they pressed against the dynamometer in the shoulder testing position. Three force measurements were recorded with a rest of one minute between measurements; the average force value was used in the analysis. After the appropriate seat adjustments were made for the elbow testing position, three force values were recorded in the elbow testing position while locking the shoulder joint and bending the elbow joint only. Again, there was a one-minute rest between recordings and the average value was used in the analysis.

The frustum sign model, the disc model and the partial frustum model provide means of calculating forearm volume using circumferential measurements of the forearm [13]. The disc and partial frustum models give the most accurate value for forearm volume, however, they require girth measurements spaced 40mm a part. A simplified and more approximated approach was employed in which the upper forearm was separated into two truncated cones using the forearm measurements, and the below formula was used [12]:

$$V = h \times \frac{(C^2 + C \cdot c + c^2)}{12 \cdot \pi}, \tag{1}$$

where V is the volume of the section (cm^3), C and c are the circumference measurements at either end of the section (cm), and h is the distance between C and c (cm). This method has shown high correlation to the water tank method [12]. The volume of both forearm sections were calculated and summed together to determine the total forearm volume for the proximal 14cm of each participant's forearm (since there was 7cm between C and c for each section).

The maximum torque was calculated with:

$$T = F \times d, \quad (2)$$

where T is torque [Nm], F is the force [N] detected by the dynamometer and d is the length [m] from the acromion to mid-palm, calculated through anthropometric data tables [14]. Similar was done for the maximum elbow joint torque, using the distance from the elbow to mid-palm. Seven of the subjects' arm lengths were manually measured giving a 6% and 0% error for acromion and elbow distances compared to [14].

III. Results

Anthropometric factors for males and females were plotted together against the maximum shoulder joint torque produced by each individual, and were analyzed using regression analysis. Polynomial and linear regression lines described most of the factors best, as they produced the highest coefficient of determination values. *Height* followed a quadratic trend and *upper forearm volume* was linear, coefficient of determination was approximately 0.6 for these factors and a significance of $P<0.001$. For maximum elbow joint torque regression analysis, the same parameters produced the highest coefficient of determination values (approximately 0.4 and 0.6 respectively) and a significance $P<0.005$. Additionally, regression analysis for males and females separately was carried out, however, lower coefficient of determination values was calculated overall (between 0.02 and 0.4). From the regression analysis, the parameters that have the greatest impact on maximum torque of the shoulder and elbow joints torque were known, males and females could be combined, and separate models for the maximum torque estimation of the shoulder and elbow joints could be created.

Using SPSS software, linear regression analysis related height (H) and upper forearm volume (UFV) to maximum shoulder joint torque and the following equation for the predicted value (x_S) described this relationship:

$$x_S = 3289.70 + 1153.97(H^2) - 3904.52(H) + 0.07(UFV) \quad (3)$$

The predicted values for each participant were plotted against the maximum shoulder joint torque ($T_{S_{MAX}}$) to produce the below chart (Fig. 3) with an r-square of 0.70, and it follows the below equation:

$$T_{S_{MAX}} = 2.76 \times 10^{-12} + x_S \quad (4)$$

The same procedure was followed for the maximum elbow joint torque model and the equation to determine the predicted value (x_E) is below:

$$x_E = 2962.00 + 1006.85(H^2) - 3469.21(H) + 0.09(UFV). \quad (5)$$

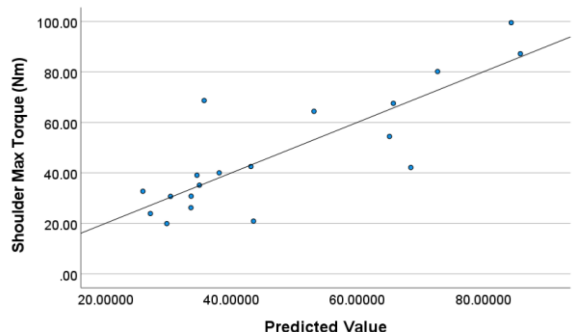

Figure 3. Linear model to estimate maximum shoulder joint torque.

The predicted values for each participant were plotted against the maximum elbow joint torque to produce the below chart (Fig. 4) with an r-square of 0.63, and it follows the below equation:

$$T_{E_{MAX}} = 7.74 \times 10^{-13} + x_E \quad (6)$$

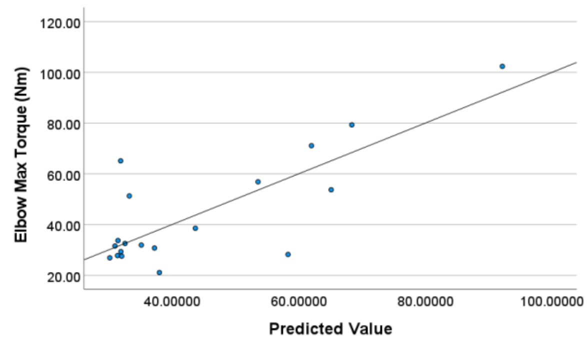

Figure 4. Linear model to estimate maximum elbow torque.

Fig. 5 and 6 show the residuals for the shoulder and elbow joint models respectively. The mean maximum shoulder joint torque was 47.69Nm and the standard deviation of the residuals was 13.05Nm for the shoulder torque regression line.

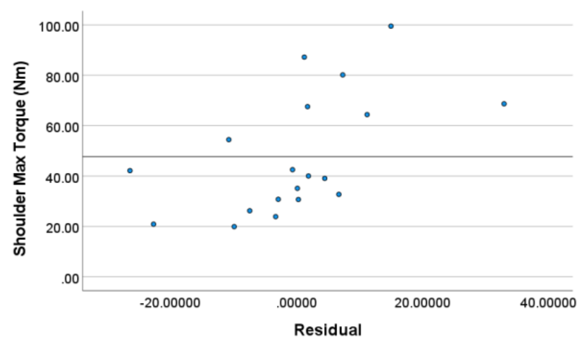

Figure 5. Residuals for the maximum shoulder joint torque model

While the mean maximum elbow joint torque was 44.18Nm and the standard deviation of the residuals was 14.22Nm.

Fig. 5 and 6 show the residuals for the shoulder and elbow joint models respectively. The mean maximum shoulder joint (flexion) torque was 47.69Nm and the standard deviation of the residuals was 13.05Nm. While the mean maximum elbow joint (flexion) torque was 44.18Nm and the standard deviation of the residuals was 14.22Nm.

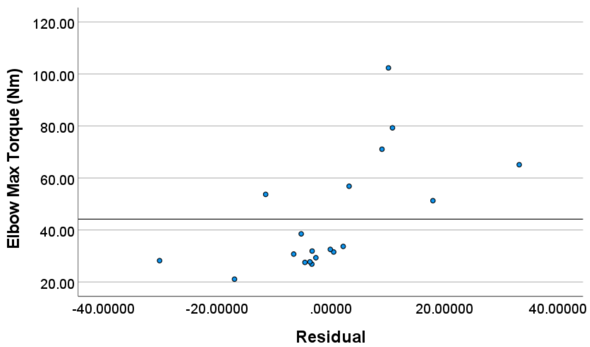

Figure 6. Residuals for the maximum elbow joint torque model.

IV. Discussions

In this work, demographic and anthropometric parameters were linked to the maximum shoulder and elbow joint torque of nineteen individuals, and two models for the estimation maximum joint torque were developed. The mean joint torque for the shoulder in flexion were lower than values reported in Otis *et al.* (approximately 70*Nm* compared to 47*Nm*) which only included male participants between 21 and 35 years [6]. Günzkofer *et al.* showed maximum elbow joint torques between 30-60*Nm* for young males and females in flexion, which is in agreement with the values reported in the present study [7]. Linear regression analysis identified *height* and *upper forearm volume* as strongly influencing joint torques of both males and females, which is in alignment with the hypothesis, however, *BMI* was not. Two separate regression models describe the combined effects of these parameters on maximum shoulder and elbow joint torques. R squared values were between 0.6 and 0.7, with a significance of $P<0.001$ for the shoulder joint model while the significance level for the elbow joint model was $P<0.005$. The residuals demonstrate there is a relatively tight fit of the recorded torques to the predicted values.

The novelty of this study does not only lie in understanding the relationship between numerous factors, but also in the identification of the most relevant factors to produce a model that estimates maximum joint torque. Identifying the minimum number of parameters needed for a reliable torque estimation, simplified the model and enabled the predicted value to be found easily and promptly without significantly compromising accuracy. A model to describe maximum joint torque means a force gauge is not required for each subject in settings outside a lab. Instead, basic anthropometric measurements are sufficient for maximum joint torque estimations using the model created in this research. It speeds up processing time of subjects and does not require specialized equipment. The number of participants and the age of the cohort remains a limitation of the study. Other planes such as shoulder axial rotation and elbow varus/valgus torques, which are commonly used in sports literature are not considered and neither are submaximal contractions. Future work may entail cross-validating the models against a large sample group to determine their accuracy and adjust the models. Wearable sensors may be used to determine whether postural positions are maintained during testing to ensure consistency between participants. The models in this paper are useful for those that utilize biomechanical data for health, safety and rehabilitation purposes, and can be used to reduce the time for processing subjects in studies that require joint torque information.

V. Conclusion

Height and upper forearm volume were found to influence maximum shoulder and elbow joint torques an individual. Models to estimate maximum shoulder and elbow joint torques were created using regression analysis. The models enable joint torque estimation for individuals using basic anthropometric measurements and do not require testing with a dynamometer.

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