

# Quantitative Estimation of Forearm Strength and Associated Muscle Fatigue on the Screw Driving Task

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## Research article

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# Abstract

**Background:** Upper extremity musculoskeletal disorders are highly prevalent work-related injuries. The problem is commonly related to tasks that involve forceful exertion and repetitive motion. This study investigated forearm muscular strength and fatigue when performing a screw driving task using the screw driving model.

**Methods:** Ten male and two female adults participated in this study. The pre- and post-fatigue maximum handgrip, driving torque, push force, insertion rate of the screws and corresponding electromyographic responses were measured to assess the muscle strength loss and fatigue of the forearm when driving screws.

**Results:** After screwing, the maximal grip force, maximal driving torque, and maximal push force losses were approximately 32%, 24% and 27%, respectively. The percentage force loss of grip force and driving torque in the brachioradialis and extensor carpi ulnaris was greater than those of the biceps brachii. The percentage of maximum driving torque and push force decreased significantly on the eighth screw compared with the first screw. The insertion rate decreased linearly with the number of inserted screws; however, a significant decrease in the insertion rate of the fourth screw was observed.

**Conclusion:** Muscle fatigue may occur in subjects who are inserting more than four screws. More muscle force loss and a higher risk of fatigue occurred in the brachioradialis and extensor carpi ulnaris. The results of this study can be used to assess the risk of forearm injury and potential for muscle fatigue due to exposure to repetitive driving tasks.

**Keywords:** muscle fatigue, maximum isometric forces, driving torque

## 1. Background

Musculoskeletal disorders are the most commonly reported work-related health problem in recent years. Most upper limb musculoskeletal disorders are cumulative disorders, resulting from manual handling, heavy physical work, uncomfortable postures, repetitive motion, vibration, exposure to high- or low-intensity loads over a long period of time or repetitive hand-tool tasks. The extent of the problem has been documented, such as tendinitis, golfer's elbow, carpal tunnel syndrome, epicondylitis, ganglionic cysts, DeQuervain's disease, white finger syndrome and tendon and tendon-related disorders [1–6].

Powered hand tools are widely used for many industrial jobs and manual hand tools and manual operations are still routinely used in some industries and trades [7, 8]. The screwdriver is one of the most commonly used hand tools employed in a number of occupations, such as machine/automobile assembly, maintenance/repair activities, gardening, construction work or woodworking tasks. Screw driving requires repetitive movements of the hands-arms, providing the power grip force to exert torque from the hands and fingers [9, 10]. Psychophysical studies have reported the maximum frequencies and forces of repetitive wrist and hand tasks [9, 12–14]. During screwing, the driving task can be described by

supination/pronation, wrist extension/flexion and radial/ulnar deviation [11]. However, this repetitive motion can induce forearm muscle fatigue and increase the risk of upper limb injury and disease, particularly in the biceps brachii (BB), brachioradialis (BR) and pronator and supinator arm muscles. It has been reported in many studies that such diseases are mainly caused from either over-exertion or repetitive/prolonged poor working postures while performing tasks [15–19].

Muscle fatigue is a common non-specific symptom experienced by many people that limits athletic performance and increases and restricts daily life [20]. It is typically quantified as a decrease in maximal force or power capacity in response to contractile activity [21–24]. The fatigue phenomenon is also reflected in the electromyography (EMG) signal as a change in its amplitude and a decrease in its characteristic spectral frequency [25–27]. Quantifying muscle fatigue is helpful to manage labour because muscle fatigue can be reduced by scheduling a fixed daily rest period. However, the physical and mental states of an individual change daily, even if the same individual is exposed to the same workload, the response generated can differ according to the time point [28, 29]. In this study, quantitative methods were used to assess forearm muscle strength and fatigue characteristics during a screw driving task to understand whether screw driving-related operations increase the risk for forearm injuries.

## 2. Methods

### 2.1. Participants

A total of 12 healthy adults (10 males and 2 females; age range: 21–38, mean age:  $26.2 \pm 6.5$  years), participated in this experiment. The body height and the weight of the subjects were  $170.5 \pm 8.6$  cm and  $67.5 \pm 13.2$  kg (mean  $\pm$  SD), respectively. All subjects were right-hand dominant without a history of hand injury. Prior to participation, all subjects were informed about and understood the details of the research, and signed an informed consent form approved by the Institutional Review Board (IRB).

### 2.2 Instrumentation

Twisting a screwdriver involves a combination of grip force (GF), driving torque (DT) or torsional moment, and push force (PF). The torsional moment is generated from the driver handle through a handgrip force and friction from the screwdriver. DT is mainly provided by the supination/pronation torque of the forearm's BR and extensor carpi ulnaris (ECU). The push force is applied to the screw to go forward during insertion. An experimental device (platform) for measuring the driving forces was constructed with two clippers, and a six-dimensional load cell (MC3A AMTI, Watertown, MA, USA) was placed underneath the specimen to measure the maximal driving torque and sub-cycling forces during screw insertion (Fig. 1). The measured force level was digitized by A/D conversion at 100 Hz (16-bit resolution) and stored on a computer for further analysis. This platform was installed on a work table for the screw driving (insertion) tasks. The height of the work table was adjusted individually based on the subject's stature. Eight stainless screws (diameter = 3.6 mm, length = 30.5 mm, and pitch = 1.0 mm), which are commonly used in woodworking, were used to insert a prismatic wood bar specimen (35 · 65 · 280 mm) using a 35-mm handle diameter screwdriver (Fig. 2). The prepared site of the wood bar specimen was previously

predrilled with nine pilot holes (hole diameter = 1.5 mm, spacing = 25 mm) to guide insertion of the screws and to prevent the wood from splitting or cracking during screwing. A steel plate (30 · 30 · 5 mm) was predrilled with a 3.6 mm screw hole at the centre of the plate, and a 3.6 mm screw was inserted into the predrilled hole of the steel plate, then the screw head was welded together with the steel plate. The bottom side of the plate was smeared with epoxy, then the screw-plate was inserted into the middle span of the wood specimen (5th hole) until the plate pressed the surface of the wood specimen, providing adherence with the specimen. This fully secured screw-plate-specimen provided a non-rotatable (fully fixed) mechanism to avoid stripping the screw (over-tightening a screw in a hole) and allowed the participant to perform isometric exercises. The two ends of the wood specimen were clipped on the experimental platform to perform the screw driving tests, and the screws were inserted into 1–4 and 6–9 pilot holes.

The maximal grip force (MGF) values before and after driving the screw were measured using a digital handgrip dynamometer (Jamar Plus + Digital Hand Dynamometer, Sammons Preston, Bolingbrook, IL, USA). A wireless surface electromyography (sEMG) measuring instrument system (Telmyo 2400R, Noraxon, Scottsdale, AZ, USA) was employed to record the myoelectric signals during force application to determine the muscle responses and fatigue. Prior to placing the electrodes, the surface of the skin above the BR, ECU and BB were cleaned with alcohol to reduce skin impedance. Bipolar Ag/AgCl surface electrodes (Kendall Meditrac 100 Tyco Healthcare Group LP, Mansfield, MA, USA) were placed in the direction of the muscle fibres with a 2.5 cm inter-electrode distance in the middle portion of the muscles. The reference electrode was placed on the latter epicondyle of the elbow.

## 2.3 Experimental procedures

Prior to the start of the screw insertion test, a wooden specimen was installed on the experimental platform, and both ends of the specimen were clipped on the experimental platform for the driving test. The height of the test table was previously adjusted to a suitable level according to the requirement of each participant. The surface electrodes were placed on the BB, BR and the extensor carpi ulnaris (ECU) of the subject. In this study, the experiment was conducted in three stages:

First, each participant was required to perform the forearm maximum voluntary isometric effort to obtain the maximal isometric forces (MIFs), including the maximal gripping force (MGF), maximal driving torque (MDT) and maximal push force (MPF) and to determine the EMG signals corresponding to these applied MIFs. During this stage, the participants repeated the MIF task three times (three trials) each. The average value of the three trials was used to determine the force values under pre-fatigue conditions  $[(MIF)_{PRE}]$ . In the second stage, each participant was required to insert eight screws into the specimen using their own driving speed. Less than 5 s of preparation time was allowed from the completion of one screw to the start of the next screw during the screw driving trial to reduce the recovery effect as much as possible. During testing, real-time information about the cyclic DT, PF, and EMG signals were continuously measured and recorded for analysis. After finishing the second stage (8-screw insertion task), the third stage of the experiment was immediately conducted. A single trial measurement was performed to obtain the post-fatigue maximal isometric force values  $[(MIF)_{POST}]$ . The measurement process during this stage

was similar to that of the first stage. The single-trial task during this stage was performed to avoid the effect of muscle recovery between trials and fatigue due to trial times.

The force loss (FL) before and after inserting the screw,  $FL = (MIF)_{PRE} - (MIF)_{POST}$ , was regarded as the degree of muscle fatigue caused by driving the screws [30]. The percentage of FL for each participant was normalised by their pre-fatigue condition ( $MIF_{PRE}$ ) as:

$$FL (\%) = \left( \frac{(MIF)_{PRE} - (MIF)_{POST}}{MIF_{PRE}} \right) \times 100 \% \quad (1)$$

Where  $MIF_{PRE}$  and  $MIF_{POST}$  correspond to the maximal isometric forces measured at the pre-fatigue and post-fatigue conditions, respectively. The measurements and data processing for the GF, DT, and PF as well as the EMG signals during the three stages are detailed in Sect. 2.4.

## 2.4 Measurement and data processing

### 2.4.1 Maximal gripping force

Prior to the screw driving experiments (first stage), each participant was verbally instructed to produce their MGF on an electronic (digital) handgrip dynamometer with an approximate 90° elbow flexion posture. This exercise was performed three times (three trials) with a 3 min break between trials to minimise the potential effect of muscle fatigue. The peak value of the GF during each trial was measured by the digital handgrip dynamometer. The average value for the three trials was recorded as the pre-fatigue maximal grip force  $[(MGF)_{PRE}]$ . After inserting the eight screws, a similar MGF trial was conducted (in the third stage) to obtain post-fatigue maximal grip force  $[(MGF)_{POST}]$ ; then, the percentage of FL in the handgrip was determined by Eq. (1).

### 2.4.2 Maximal driving torque

A 3 min rest was taken after completing the maximal grip force measurements; then, three trials of the maximal isometric driving torque tasks were performed on the head of the fifth screw to obtain pre-fatigue maximal isometric driving torque. The participants used a screwdriver to exert the driving torque from zero to a maximum in 3 s and held the maximal force for approximately 3 s. The steady-state part (holding period) of the measured values during the 1 s time window was used as the mean driving torque of the trial. This removed any influence of the start of the plateau contraction and the ramping up to MIF. The values from the three trials were averaged and used as the maximal driving torque before the operation  $[(MDT)_{PRE}]$ . A post-fatigue trial (third stage) was performed with similar processing to obtain the post-fatigue maximal driving torque value  $[(MDT)_{POST}]$ .

### 2.4.3 Maximal push force

After completing the maximal driving torque test and after a 3 min break, the maximal push force (MPF) was determined in three trials to obtain the pre-fatigue condition of the PF. Participants practised their MPF at the head of the fifth screw and maintained it for approximately 3 s. During isometric pushing, force generation data were measured and recorded for analysis. As mentioned above, a similar approach was used to evaluate the MPF (during a 1 s time window for the steady part of the measured values). Pre-fatigue maximal push force  $[(MPF)_{PRE}]$  was evaluated by averaging the three mean PF from the trials. After inserting the screw, another single trial using the same measurement process was performed to obtain the post-test maximum push force value  $[(MPF)_{POST}]$ .

## 2.4.4 EMG amplitude

When the surgeons were performing the MIFs and screw driving tasks, sEMG signals (in mV) were simultaneously collected during the BR, ECU and BB activities. The EMG signals were amplified (gain 1000·) and were digitally filtered using a bandwidth of 20–300 Hz (Butterworth filter), A/D converted at 1,000 Hz and stored on a computer for subsequent analyses. The amplitude of the root mean square (RMS) value of the EMG signal was used to analyse the muscle response [31–39]. During the first stage of our study, each MIF task was conducted in three trials. The EMG amplitude (in micro-volts) RMS values were calculated at 1 s intervals for each actual trial. The average value of the three EMG values calculated from each maximal isometric force (pre-fatigue) task was used to normalise the EMG data collected from the MIF tasks. In this study, the EMG RMS values that corresponded to the MIF tasks before and after the screw insertion tasks that corresponded to the MIF measurement are presented as  $(EMG)_{PRE}$  and  $(EMG)_{POST}$ , respectively. Thus, the percentage change in EMG amplitude before and after inserting the screw was expressed as:

$$\Delta \text{EMG (\%)} = \left( \frac{EMG_{POST} - EMG_{PRE}}{EMG_{PRE}} \right) \times 100 \% \quad (2)$$

## 2.4.5 Insertion forces during cycling

Muscle fatigue is defined as a gradual decrease in the force capacity of a muscle or the duration in which a given level of maximal voluntary contraction (MVC) can be sustained; it can be measured as a reduction in muscle force, as a change in EMG amplitude or characteristic frequency or as exhaustion of contractile function [40, 41]. Figure 3 shows a schematic of the repetitive exertion (sub-cycle) when inserting a screw. The screwing operation was performed in a repetitive hand-arm movement with a dynamic force act, and muscle contraction was not continuously sustained at a constant level; it was therefore not easy to quantify the degree of muscle fatigue.

In this study, the impulse produced during the  $i$ th sub-cycle ( $I_i$ ), where driving time  $t_i$  is defined as the integral of the applied force,  $f(t)$ , over the time interval,  $dt$ , for which it acts, was calculated from:

$$I_i = \int_0^{t_i} f(t) dt \quad (3)$$

Where:

$I_i$ : impulse during the  $i$ th sub-cycle

$f(t)$ : applied force (measured driving torque or push force) at time  $t$

$t_i$ : time duration of the force acting (driving time) at  $i$ th sub-cycle

The cyclic exertion during the  $j$ th screw is analogous to an average insertion force ( $F_{j-avg}$ ) generated over the  $j$ th insertion time ( $T_j$ ), which was obtained by:

$$F_{j-avg} = \frac{\sum_{i=1}^n I_i}{T_j} \quad (4)$$

Where:

$F_{j-avg}$ : average applied force to insert the  $j$ th screw

$j$ : screw number

$n$ : number (times) of sub-cycles when inserting a screw

$T_j$ : time duration for inserting the  $j$ th screw, which was calculated by summing the driving time of each sub-cycle

$$(T_j = \sum_{i=1}^n t_i).$$

The insertion rate (IR) is similar to the power (work done per unit time) and is used to quantify the diminishing performance trend across the eight repetitions of screwing and to evaluate the fatigue characteristics of the forearm during repeated driving tasks. The insertion rate (IR) of the  $j$ th screw was:

$$IR_j = \frac{F_{j-avg}}{T_j} \quad (5)$$

However, the insertion force,  $F_{j-avg}$ , includes the combination of two components: DT and PF. Therefore, the term ( $F_{j-avg}$ ) in Eq. (4) and Eq. (5) should be expressed as  $DT_{j-avg}$  and  $PF_{j-avg}$  for average driving torque and average push force, when inserting the  $j$ th screw, respectively.

## 2.5 Statistics

SPSS statistical software (SPSS 13.0; SPSS Inc., Chicago IL, USA) was used to conduct the paired t-test to investigate differences in GF, DT, PF and the EMG signal in the MIF under pre- and post-fatigue conditions. A p-value < 0.05 was considered significant.

## 3. Results

Table 1 summarises the measured values of MGS, MDT and MPF at the pre- and post-fatigue conditions for the subjects. The force loss values presented in Table 1 were calculated using Eq. (1). The results show the average percentages of force loss for GS, DT, and PF, which were 32.1%, 24.2% and 26.5%, respectively. The overall loss of handgrip force, DT, and PF was significant at the  $p < 0.001$  level. Each participant had a loss of hand gripping force compared to DT and PF after performing the screw driving tasks, indicating that muscle fatigue may have occurred in this study.

Table 1  
Summary of force loss (FL %) results for the participants

Subjects	Max. Grip Force			Max. Driving Torque			Max. Push Force		
	PRE-(N)	POST-(N)	FL (%)	PRE-(N-m)	POST-(N-m)	FL (%)	PRE-(N)	POST-(N)	FL (%)
S 1	508.2	318.6	37.3	6.1	4.4	27.9	141.3	98.5	30.3
S 2	441.5	271	38.6	3.9	2.7	30.8	137.6	107.9	21.6
S 3	453.2	308	32.0	5.1	3.8	25.5	144.3	105.6	26.8
S 4	390.4	280.1	28.3	5.9	4.2	28.8	148.4	109.5	26.2
S 5	440.8	296.2	32.8	4.7	3.3	29.8	138.2	90.7	34.4
S 6	383.5	269.4	29.8	5.3	4.0	24.5	125.5	92.7	26.1
S 7	485.6	315.5	35.0	4.9	3.8	22.4	126.9	97.4	23.2
S 8	316.3	234.9	25.7	5.1	4.0	21.6	135.7	99.8	26.5
S 9	325.4	206.7	36.5	4.8	4.3	10.4	140.9	100.6	28.6
S 10	346.8	225.6	34.9	5.7	4.2	26.3	120.8	89.4	26.0
S 11	413.6	300.8	27.3	6.2	5.1	17.7	131.9	100.6	23.7
S 12	408.8	300.7	26.4	4.9	3.7	24.5	140.3	105.7	24.7
Average	409.5	277.3	32.1	5.2	4.0	24.2	136.0	99.9	26.5
(St. Dev.)	60.4	37.1	4.5	0.7	0.6	5.7	8.2	6.6	3.4
P-value	P < 0.001 *			P < 0.001 *			P < 0.001 *		
* Statistical significance of the maximal isometric forces (MIFs) between the pre- and post-fatigue conditions with a p-value < 0.05									
Values in brackets are standard deviations									

The percentages of applied DT and PF for the first, fourth and eighth screws relative to the pre-fatigue MIF value were analysed using Eq. (5). The effect of the inserted screw number on applied DT and PF is shown in Fig. 4. The DT percentages for the first, fourth and eighth screws were 13.6%, 12.1% and 6.7%, respectively, and they were 14.8%, 11.6% and 7.0%, respectively for PF. Significant differences were found between the first and eighth ( $p < 0.001$ ) and fourth and eighth ( $p < 0.001$ ) screw driving operations in terms of DT and PF. However, no significant difference was observed between the first and fourth DT ( $p = 0.123$ ).

The IR represents the force generated per unit time while inserting one screw, which was calculated by Eq. (6). The applied forces (DT and PF) of the first screw were normalised as the baseline for the following sequence insertion forces. The rate of decline of applied force from the first screw across the eight screw repetitions was evaluated using regression data fitting. Figure 5(A) and 5(B) shows the DT and PF generated per minute for the insertion of each screw. A linear relationship was detected between the DT insertion rate (IR) and screw number ( $R^2 = 0.9791$ ). Similar results were also observed for the IR of PF with screw number ( $R^2 = 0.9669$ ). The fourth screw had a significantly decreased IR compared with the first screw.

Muscle fatigue characteristics during contraction are also be reflected in EMG signals. Figure 6(A) shows the average EMG amplitudes for the participants' BB, BR and ECU relative to the change in maximal grip force ( $\Delta\text{EMG} \%$ ) before the screw insertion operation, as obtained from Eq. (2), with values of 17.4%, 28.1% and 29.7%, respectively. The percentage variation in the EMG for these three muscles were 16.7%, 39.3% and 37.3%, respectively, for the MDT test [Fig. 6(B)] and 36.5%, 29.4% and 34.1%, respectively, for the MPF test [Fig. 6(C)]. The BR and ECU exhibited significant changes in EMG amplitude compared to the BB muscle.

## 4. Discussion

Voluntary muscle strength must be assessed to determine optimal human work capacity. Overexertion is considered a major factor causing musculoskeletal injuries. High force for a working requirement has been identified as a risk factor for hand-wrist cumulative trauma disorders [5]. The present study experimentally investigated the risk of forearm musculoskeletal disorders while driving screws. During the screw driving task, the muscles involved concurrently exerted torque about the pronation–supination axis of the forearm combined with ulnar deviation of the hand under elbow flexion. Inserting a screw involves applying three force types simultaneously: the subject must hold the handle of the screwdriver and apply a combination of forearm torsion with a pushing force to insert the screw. The three force types, GF, DT and PF, are the major forces acting during a driving task. Changes in the MIF and EMG signal amplitude before and after inserting a screw were used to evaluate forearm muscle strength and fatigue in subjects. Our experimental results showed that after the subjects inserted eight screws, the MGF, MDT and MPF decreased by an average of 32%, 24% and 27%, respectively, with GF showing the most substantial FL.

We designed an eight screw driving task to investigate intensity of muscle activity (FL). Figure 5(A) and 5(B) show that the percentages of MIF (pre-fatigue) relative to DT and PF during screwing decreased from 13.6% (0.72 N m) to 6.7% (0.35 N m) and from 14.8% (20.11 N) to 7.0% (9.54 N), respectively. Both forces applied on the eighth screw were reduced by approximately half of that applied to the first screw. According to the DT and PF measured for the first, fourth and eighth screws, an approximate linear decrease in force was observed as the number of screws inserted increased.

The screwdriver used in this study had a cylindrically shaped handle and a circular cross-section that is comfortable to hold in the hand. Some studies have reported that discomfort in handle shape, handle size

and handle material may reduce the GF and DT and cause hand-arm musculoskeletal disorders [42–51]. The handle of the screwdriver was made of polypropylene with hardness similar to that of the human hand, providing a comfortable holding sensation. In some situations, gloves are used to protect the hands from human/tool hazards. Wearing gloves reduces the friction between the hand and the hand–tool surface as well as prevents localised hand discomfort [52]; thus, industrial gloves are designed with greater thickness to protect the hands from injuries. Swain et al. [53] reported that wearing industrial gloves reduces torque exertion when operating knobs. Mital et al. [42] showed that gloved supination/pronation during maximum volitional torque exertion (MVTE) is greater than barehanded MVTE when operating a screwdriver.

Muscle fatigue is complex with important implications for ergonomics. It can be defined as a decrease in maximal force or power production in response to contractile activity of a muscle. When fatigue occurs, maintaining the same force level becomes difficult; thus, increasing the likelihood of sustaining an injury. To measure the degree of muscle fatigue is a challenge as it cannot be easily quantified, particularly as it increases significantly during repetitive motion. Several studies have measured the time to failure to assess muscle fatigue while subjects sustained an isometric contraction [54, 55].

Soo et al. [56] proposed a recovery model to establish the relationship between muscle fatigue and rest time. They used a maximal isometric grip force of 50% for 10, 30 and 50 s to explore the effect with/without recovery on fatigue, and recovery during the operation was crucial to relieve muscle fatigue. Some studies have investigated fatigue characteristics using isometric muscle contractions; however, muscles are not persistently in the state of isometric contraction during dynamic work because muscle recovery occurs simultaneously. Our study evaluated muscle fatigue during a screw insertion operation in a dynamic environment. The muscle fatigue characteristics were not analysed using long-term, accumulated data because a short rest period was taken between screws to recover from muscle fatigue; rather, they were analysed using MVC and EMG variations before and after driving the screws.

The degree of muscle fatigue can be estimated based on the physiological and biomechanical signal changes in the muscles during fatiguing contractions. Surface EMG (sEMG) has been widely used as a non-invasive technique to quantify the level of total activity of working muscles and to identify muscle fatigue. Although this study only measured the skin sEMG signals of muscles during which cross-talk interference of the underlying adjacent muscles still occurred, EMG has become a popular tool for assessing muscle responses owing to its application advantages in situ, as well as non-invasive and real-time monitoring. This study only explored the immediate risks of BB, BR and ECU injuries related to the force applied while using a screwdriver. Figure 6(A) shows that the loss of EMG amplitude ( $\Delta$ EMG) was higher in the BR and ECU than that in the BB when the subjects performed the MGF test after the screw insertion operation. This finding indicates that the percentage of muscle FL in the BR and ECU was greater than that in the BB owing to the grip force applied on the screwdriver handle during screwing. Figure 6(B) also shows that the percentages of muscle FL in the BR and ECU were larger than that in the BB, indicating that the BR and ECU experienced a greater muscle loss percentage during DT than did the BB. Therefore, the BR and ECU were more likely to be fatigued than the BB in terms of GF and DT during

insertion of the screws. Additionally, Fig. 6(C) shows that the muscle FL percentage of the BB increased to 36.5% because a downward vertical force had to be applied during screw insertion. At this point, the participants had to lift their upper limbs and engage in elbow flexion (this force is mainly derived from contraction of the BB) to provide a downward force. Therefore, the PF shown in Fig. 6(C) on the BB muscle ( $\Delta$ EMG) is greater than that of the GF [17.4% in Fig. 6(A)] and DT [16.7% in Fig. 6(B)]. This study suggests that the PF caused more force loss and fatigue to the BB than the GF and DT during the screw driving task.

When performing the driving task, the applied force varied with time, unlike typical fatigue tasks in which subjects are asked to perform at a given intensity until failure. The participants adopted a self-selected technique, operating time, operating process and posture based on personal physiological conditions, and they may have spontaneously decreased the forces exerted and extended the operating time to avoid excessive local muscle fatigue. This extended time recovered the motor deficit; thus, potentially increasing the time to exhaustion from the muscle force. Although exertion force is not maintained at a constant level during sub-cycling, Eq. (5) provided the average forces for inserting a screw to estimate muscle fatigue of the dynamic (cyclic) tasks. In our study, the average DT and PF values for the eighth screw were reduced by approximately half of that of the first screw (from 13.6–6.7% and from 14.8–7.0%, respectively) (Fig. 4). Significantly different IR values were found beginning with the fourth screw, implying that forearm muscle fatigue may have developed in the subjects when inserting four screws.

Ciriello et al. [57, 58] reported that the average maximum acceptable torque (MAT) for males was between 1.15 and 1.88 N m, with an approximate ratio of 15–35% relative to maximal isometric torque. For females, the MAT was between 0.33 and 0.65 N m with ratios of 14–24%. However, they recommended values that were 75% (0.62–1.02 N m, with ratios of 14% and 11%) of their present findings for practical implications. In our study, the participants included 10 male and 2 female adults, and the average percentages of DT relative to the MDT for the first, fourth, and eighth screws were 13.6%, 12.1% and 6.7% and the corresponding applied driving torque values were 0.72, 0.58 and 0.33 N m, respectively. The measured DT of the participants during screw insertion did not exceed the maximum acceptable torque for males except the first screw. Although our experimental results did not show that the subjects had a high risk of forearm muscle injury after performing this type of screw insertion task, the current study performed the screw driving tasks under the cyclic (dynamic) action condition. As mentioned above, subjects may have spontaneously decreased the forces exerted and extended the operating time to avoid excessive local muscle fatigue. The lower force or torque and extended operating time could have recovered muscle activation and decreased fatigue during the sub-cycles. Furthermore, the two females involved in our experiment contributed smaller measured applied force values during the experiments compared with the male subjects. Therefore, this decreased total driving torque. The possible risks faced by female subjects that perform these types of screw driving tasks should be further studied.

The experiments in this study were relatively limited. Although many factors can affect insertion torque, such as the geometry of the driver handle, screw type, insertion depth, screw length, thread pitch, density, major/minor (outer/inner) screw diameters and pilot-hole size [59–63], the findings of this study were

based on the experimental results of eight screws (diameter = 3.6 mm; length = 30.5 mm and pitch = 1.0 mm). This screw type is frequently used in industry, wood working, modular furniture and construction. Other screw types, the operating technique and physical work exposure were not quantified in this study.

## 5. Conclusions

The major findings of this study emphasize the influence of forearm muscle strength and fatigue when screw driving. Our investigation shows that force losses for GF, DT and PF were approximately 32%, 24% and 27%, respectively. Both the DT and PF decreased with an increase in the number of screws inserted; the screw insertion rate decreased linearly with the number of screws inserted. The BR and ECU experienced a greater percentage of muscle fatigue than the BB. A significant difference in the screw driving tasks was observed when comparing the pre- and post-MIF tests and the IR, indicating that muscle fatigue may have occurred in subjects who inserted more than four screws. This study presents a risk assessment of forearm injury and potential for muscle fatigue due to exposure to repetitive driving tasks. More studies on the effects of gender, short and long duration effects and handle shapes of the driver on muscle fatigue and risk of forearm injuries need to be explored in the future.

## Abbreviations

biceps brachii (BB)

brachioradialis (BR)

extensor carpi ulnaris (ECU)

electromyography (EMG)

Institutional Review Board (IRB)

Standard deviation (SD)

maximal isometric forces (MIFs)

grip force (GF)

driving torque (DT)

push force (PF)

maximal grip force (MGF)

surface electromyography (sEMG)

force loss (FL)

insertion rate (IR)

maximum volitional torque exertion (MVTE)

maximum acceptable torque (MAT)

maximal grip force (MGF)

maximal voluntary contraction (MVC)

## **Declarations**

### **Ethics approval and consent to participate**

All subjects were informed about and understood the details of the research, and signed an informed consent form. This study was approved by the Institutional Review Board (No. EMRP-106-107)

### **Availability of data and materials**

All experimental data and materials used in this study appear in the submitted article.

### **Competing interests**

There is no any competing interest regarding the publication of this paper.

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### **Authors' Contributions**

C-K Hsiao participated in the study design, carried out the biomechanical study, participated in the sequence alignment, interpreted the results, and drafted the manuscript. Y-K Tu and Y-J Tsai participated in the experimental alignment and performed the biomechanical test, results analysis and statistical analysis. C-Y Yang and C-W Lu conceived the idea for the study/publication, planning of the whole study and revised the manuscript. All authors read and approved the final manuscript.

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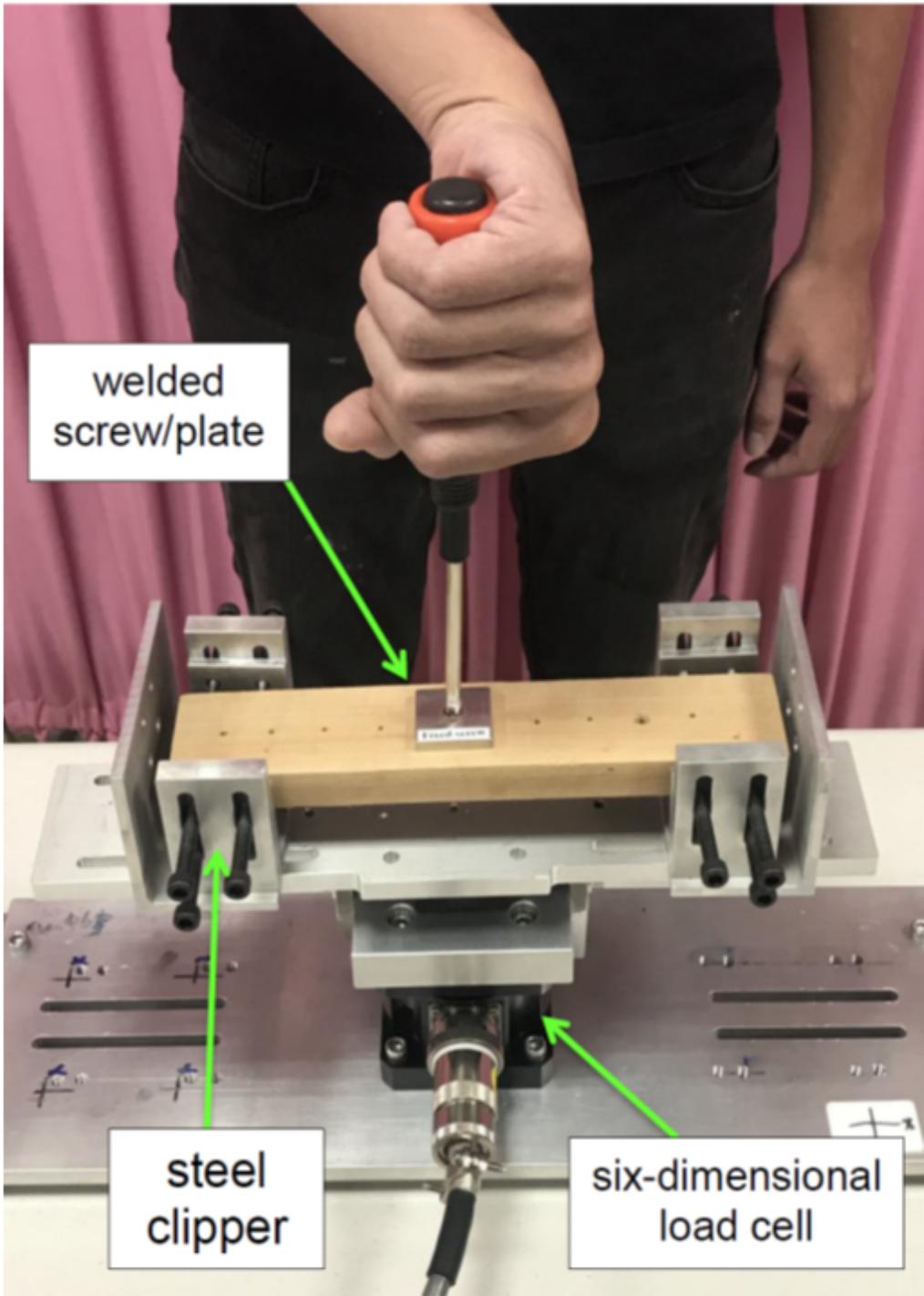
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## Figures



**Figure 1**

Experimental setup: wood specimen was fixed using two steel clips and a six-dimensional load cell was installed under the specimen to measure the applied force.

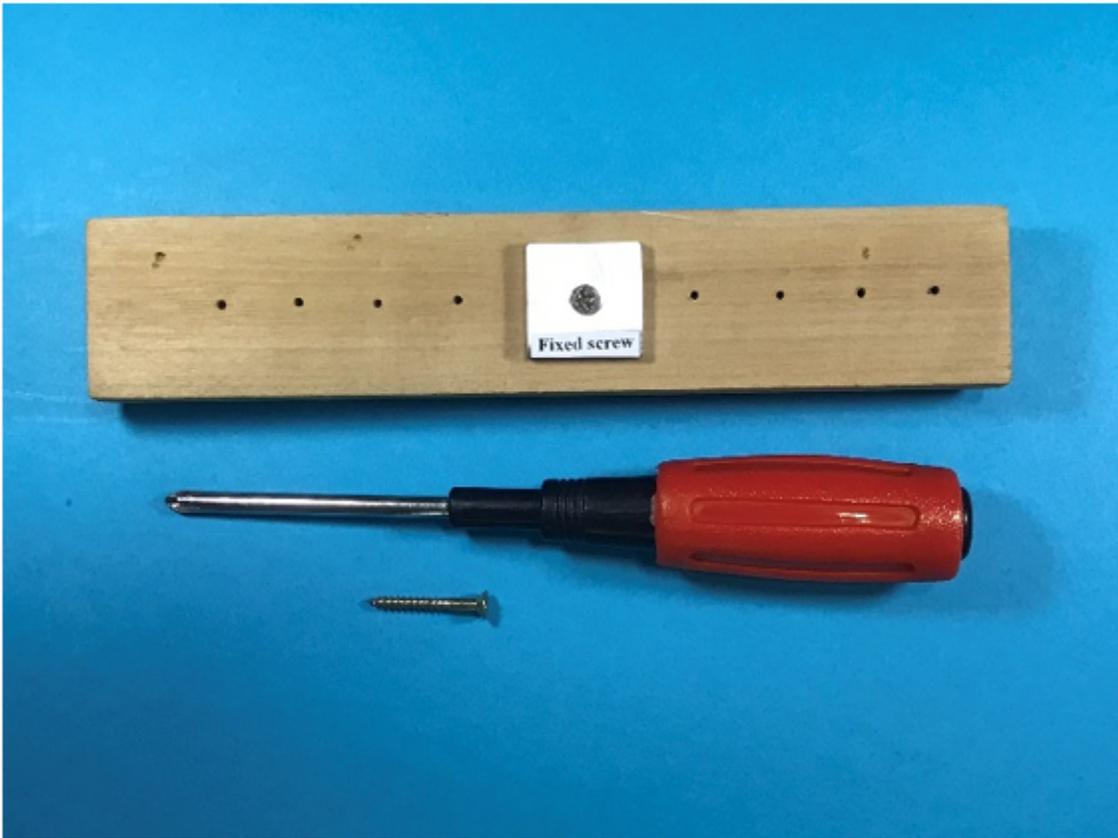


Figure 2

Prismatic wood bar specimen and screwdriver (a screw was previously welded with a steel plate and placed on the fifth hole of the specimen, and epoxy was used to mount it)

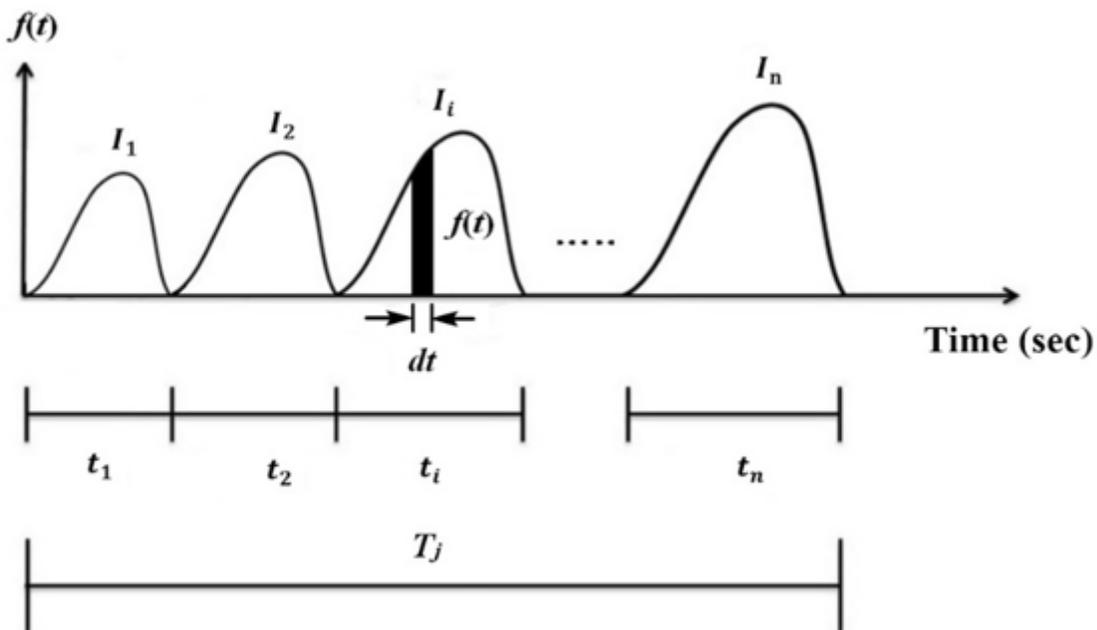


Figure 3

Schematic curve of repeated sub-cycling with time during insertion of a single screw

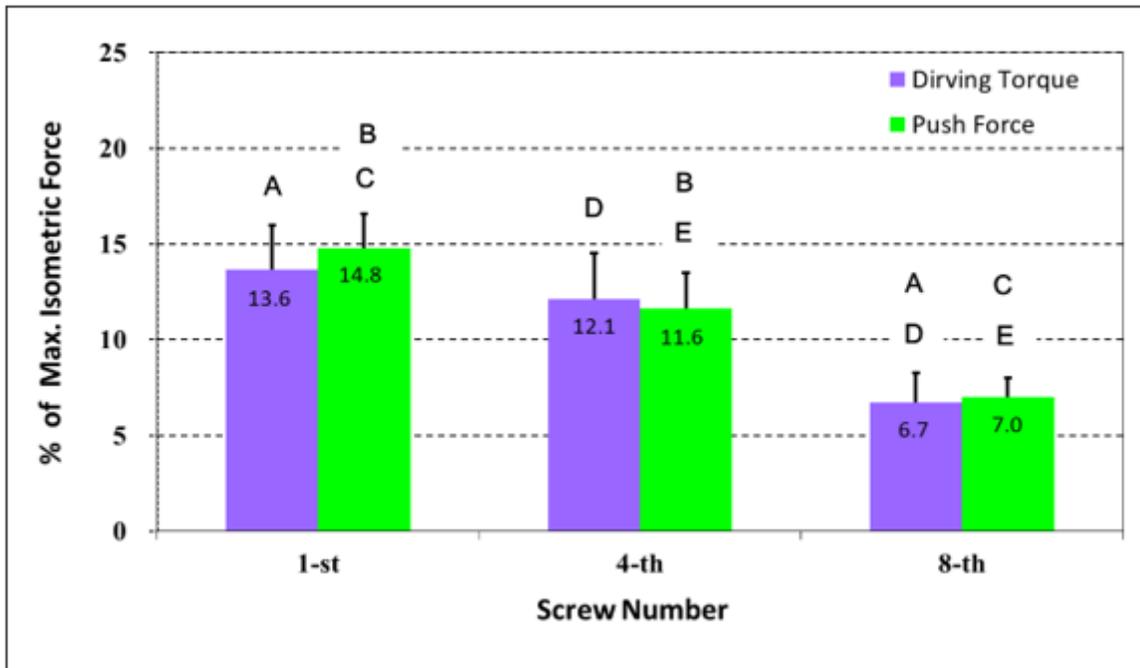
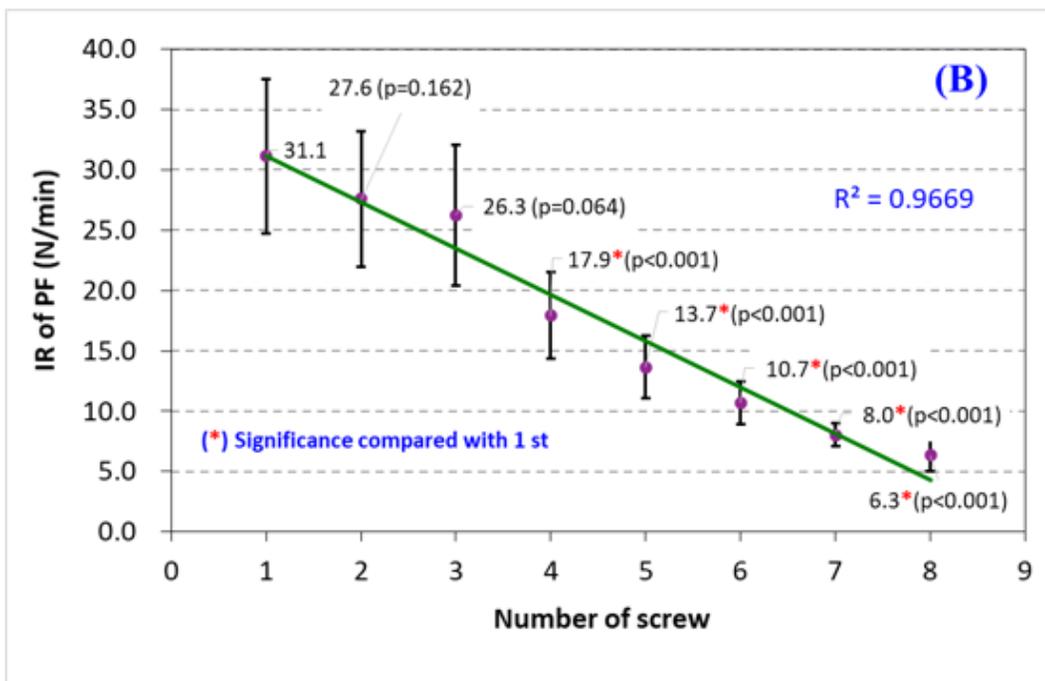
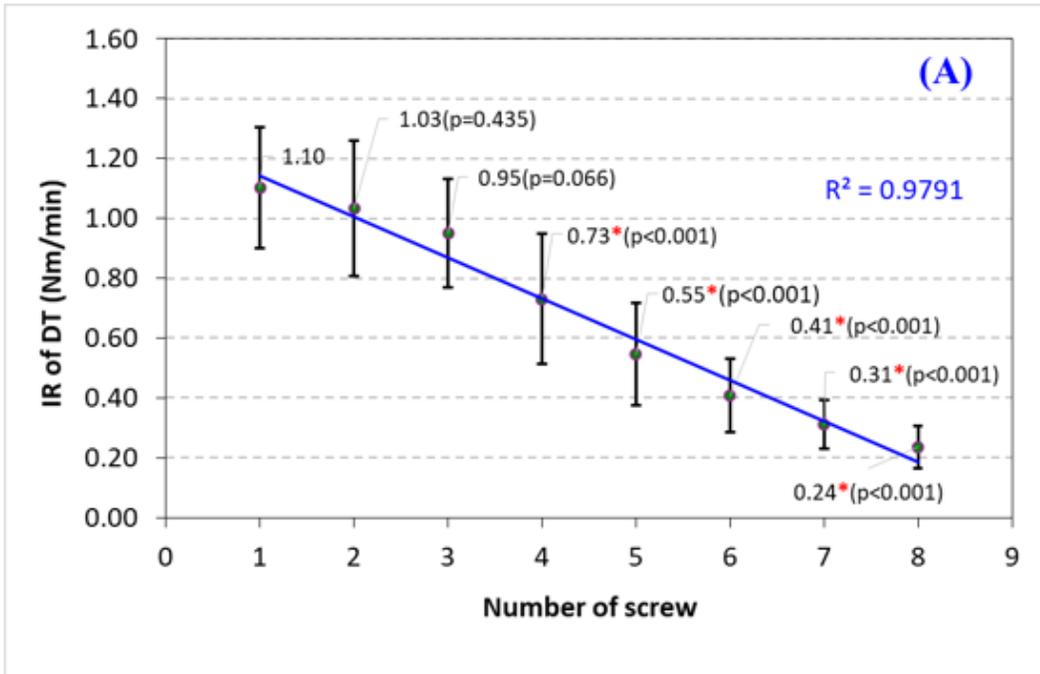


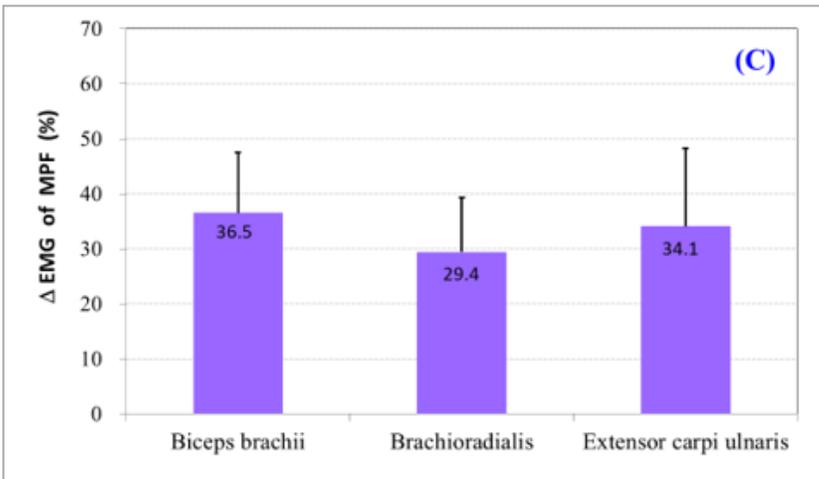
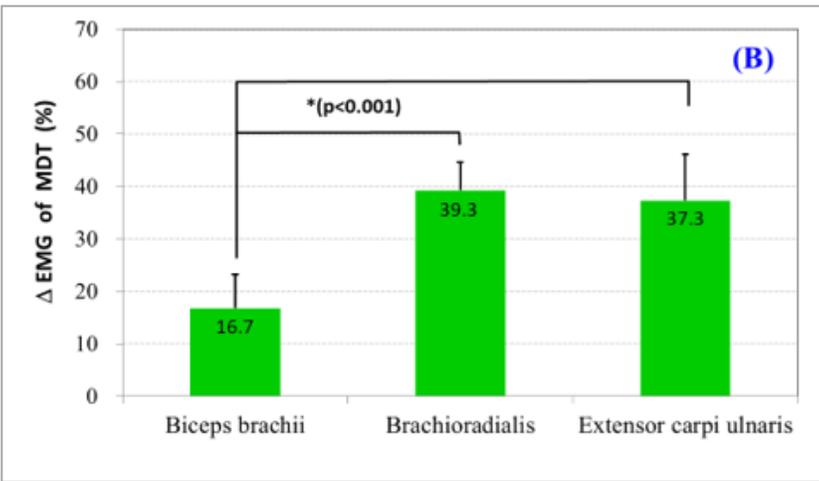
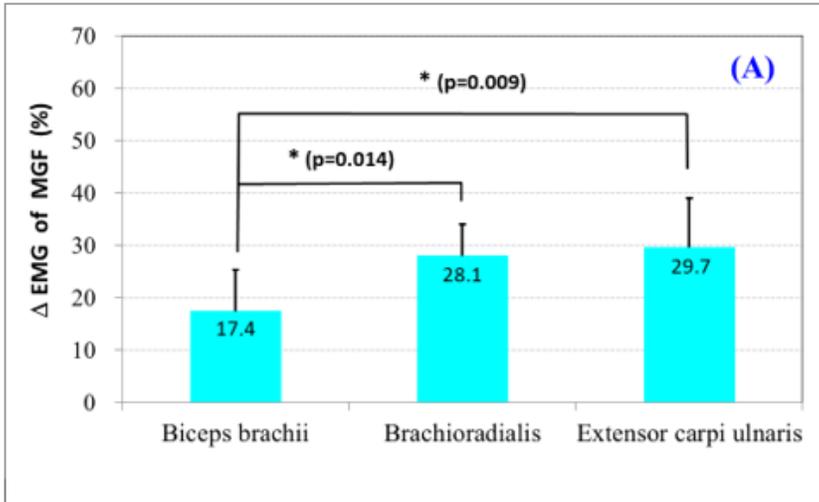
Figure 4

Driving torque (DT) and push force (PF) percentages for the first, fourth, and eighth, screws relative to the pre-fatigue maximal isometric force (MIF) value. Letters indicate significantly different screw numbers



**Figure 5**

Insertion rate decreased with screw number: (A) Insertion rate of driving torque; (B) Insertion rate of push force



**Figure 6**

EMG amplitude changes in the biceps brachii, brachioradialis, and extensor carpi ulnaris during the three maximal force conditions: (A) Maximal grip force; (B) Maximal driving torque; (C) Maximal push force