

# Effect of Push-up Speed on Elbow Joint Loading

Paul Pei-Hsi Chou<sup>1,2,3</sup> Hsiu-Hao Hsu<sup>4</sup> Shen-Kai Chen<sup>1,2</sup> Su-Kuan Yang<sup>5</sup>

Chia-Ming Kuo<sup>6</sup> You-Li Chou<sup>6,\*</sup>

<sup>1</sup>Faculty of Sports Medicine, Kaohsiung Medical University, Kaohsiung 80708, Taiwan, ROC

<sup>2</sup>Department of Orthopedic Surgery, Kaohsiung Medical University Hospital, Kaohsiung 80708, Taiwan, ROC

<sup>3</sup>Department of Orthopedic Surgery, Kaohsiung Municipal Hsiao-Kang Hospital, Kaohsiung 81267, Taiwan, ROC

<sup>4</sup>Department of Engineering Science, National Cheng Kung University, Tainan 70101, Taiwan, ROC

<sup>5</sup>Department of Sports and Recreation Management, Chang Jung Christian University, Tainan 71101, Taiwan, ROC

<sup>6</sup>Institute of Biomedical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, ROC

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## Abstract

Push-up is a common exercise used for strengthening the upper extremity muscles. Knowledge of elbow kinematics and kinetics may be helpful in preventing injuries due to push-ups if the elbow shear force can be reduced. Therefore, the purpose of this study was to investigate the effect of different push-up speeds on elbow joint loading. Fourteen healthy male graduate students volunteered for this investigation. In a motion analysis laboratory, the Expert Vision motion system with eight 240 Hz cameras and 1000 Hz Kistler force plates were used to measure relative joint positions and ground reaction forces. The surface electromyography (EMG) was used to measure the signals of muscle activity. Each subject performed push-ups in three different conditions that were pre-determined: fast speed (7 push-ups/10 s), regular speed (5 push-ups/10 s), and slow speed (4 push-ups/10 s). The kinematics and kinetics data were obtained from the Expert Vision motion system. The joint angles, resultant forces and moments of the elbow at different push-up speeds were calculated by laboratory-developed software. The peak elbow medial shear force and compression force in the fast group were 1.35 and 1.23 times greater than those in the slower group, respectively. In addition, the peak valgus moment, extension moment, and pronation moment at fast push-up speed were 1.63, 1.34 and 1.41 times greater than at slow speed, respectively. Additionally, performing the push-up more slowly could significantly increase the muscle activations in triceps brachii, biceps brachii, and posterior deltoid muscle groups, and thus be of greater benefit in muscle training. Therefore, performing the push-up exercise more slowly may be a better strategy for strengthening the upper extremity muscles.

**Keywords:** Push-up, Elbow, Biomechanics, Motion analysis

## 1. Introduction

In recent years, fitness training and bodybuilding have become increasingly popular, with push-ups being one of the most popular exercises to strengthen the upper extremity muscles [1]. The popularity of push-ups is due to the convenience of the exercise, its short learning curve, and its easy adaptability to various difficulty levels. It is commonly an essential part of fitness programs for health-conscious people and athletes. An et al. investigated the loads across the wrist, elbow, and shoulder joints during a push-up in an experimental setup [2]. Factors that affect the intersegmental loads on the joints during a push-up include the location of the palm relative to the shoulder joint, the plane of arm movement, and

the relative foot positions. In a study by Donkers et al., the hand position of "superior" (i.e.; the hands moved so that the distance between them is the same as previously, but the distance between hands and feet is increased by a distance of 50% shoulder width) resulted in greater valgus moment [3].

Attention must be given to the valgus torque encountered during push-up experiments. Clinically, the biomechanical studies have suggested that patients with medial collateral ligament (MCL) repair, radial head reconstruction, and total elbow arthroplasty should avoid exercises such as push-ups immediately after treatment [3-4]. The MCL of the elbow is an important stabilizer for varus-valgus stress [5-8]. The MCL is noted as the primary constraint, while the humeral head is the secondary constraint for valgus stability of the elbow with a tracking device in a model simulating active motion and muscle activity by Morrey et al. [9]. The elbow may be dislocated posterolaterally or posteriorly by moderate external rotation or hyper-supination (40°) and slight valgus (15°) while flexing and applying an axial compressive load [10]. Morrey et al.

\* Corresponding author: You-Li Chou  
Tel: +886-6-235-2645; Fax: +886-6-275-0621  
E-mail: ylchou@mail.ncku.edu.tw

stated that combination of increased axially directed force exerting on the radial head and the increased valgus torque experienced during a one-handed push-up would simulate a mechanism of injury [11]. Lou et al. showed that there was an increase in elbow joint loading with forearm rotation during the push-up experiments [12]. Chou et al. measured the elbow load during one-handed push-up experiments with three forearm positions and evaluated the corresponding potential trauma mechanisms of the outstretched hand [13]. The result showed that when the forearm was rotated 45° externally, the peak valgus shear force was 50% greater than that when the forearm was either in a neutral position or rotated 45° internally. Thus, outward rotation of the hand is a stressful position that should be avoided during one-handed push-up exercise in order to reduce the risk of elbow injuries.

Previous studies have investigated the relationship between push-up posture and joint loading of the upper extremity [3,7-8,12]. Chapman et al. demonstrated that fast-velocity lengthening contractions may induce greater muscle damage than slow-velocity contractions [14]. However, there is little information on the relationship between the push-up speed and elbow joint loading. Knowledge of elbow kinematics and kinetics may be helpful in reducing the elbow joint loading if the relationship between the push-up speed and joint loading could be understood. Therefore, the purpose of this study was to investigate the effect of different push-up speeds on elbow joint loading in the push-up exercise. The results of this study may provide a better strategy for strengthening the upper extremity muscles.

## 2. Methods

### 2.1 Subjects and experimental protocol

Fourteen physically healthy male graduate students volunteered for this investigation. They ranged from 19 to 26 years ( $24.5 \pm 1.4$ ) of age, from 50 to 80 kg ( $65.9 \pm 7.2$  kg) in body weight, and from 160 to 184 cm ( $168.9 \pm 5.3$  cm) in body height. All subjects were right-hand dominant, free of any musculoskeletal disorders of the upper extremities.

The Expert Vision motion system (Motion Analysis, Santa Rosa, CA, USA) includes eight 240-fps cameras used to acquire relative joint positions and one 1000-Hz sampling rate Kistler force-plate (Type 9281B, Kistler Instrument, Winterthur, Switzerland) used to measure ground reaction forces. The 1000-Hz sampling rate surface electromyography (EMG) (MA300, Motion Analysis Corp., USA) was used to measure the signals of muscle activity at different push-up speeds.

As shown in Fig. 1, a set of eleven reflective markers was placed on selected anatomic landmarks on the right side of the test subject. The selected anatomic landmarks were intended to simulate the rigid body assumption for trunk (C7, T4 and AC), upper arm (AC, ME and LE), forearm (ME, LE, RST and UST), and hand (RST, UST and MTC3). Since the distance and anatomical relationship between the mid-point of two acromion markers and the actual chest lowest point over the sternum would not change during push-up, the position of the chest

could be determined by the acromion markers, without a specific marker on the chest. In addition, a triangular frame with three-markers (U-P-M, Fig. 1) was placed on the upper arm in order to minimize potential errors due to skin movement of the epicondyles during the push-up experiments. The shoulder joint center was defined as starting at the elbow joint center (calculated by medial and lateral markers) to nearly 90% of the length from the elbow joint center to the marker at the acromion [15].

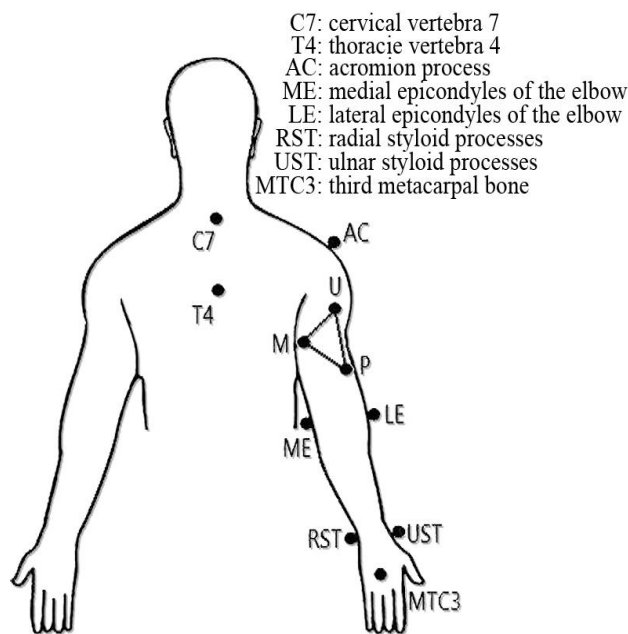


Figure 1. Rear view posture of reflective markers on bony anatomical landmarks.

Electromyographic sensors were attached to the supinator, pronator teres, triceps brachii, middle deltoid, biceps brachii, anterior deltoid, pectoralis major, and posterior deltoid for muscle activation measurement during push-up experiments. After the placement of EMG electrodes and reflexive markers, subjects were asked to perform the maximum voluntary isometric contractions (MVIC). The MVIC value for each muscle group was recorded during a series of 3-second resisted maximum contraction exercises that were designed to evoke maximum voluntary contraction for each muscle group before performing the push-up experiment [16]. Then, the subsequent EMG data during push-up experiment were divided by the MVIC value as %MVIC.

At the beginning of push-up experiment, the subjects were asked to keep the elbow joints in full extension and position their hands with a forearm axially non-rotated posture. The hand width was set to 1.5 times the shoulder width, and the feet were shoulder-width apart as initial posture. An electronic metronome was used to regulate the push-up cadence. Each subject was instructed to perform the push-ups under the beat of the electronic metronome in three different conditions that were pre-determined: fast speed (84 beats/min; 7 push-ups/10 s), regular speed (60 beats/min; 5 push-ups/10 s), and slow speed (48 beats/min; 4 push-ups/10 s). Each subject was instructed to perform the first set of push-up experiment at

fast speed within approximately 15 seconds. Five minutes was allowed for rest between sets, in order to avoid muscle fatigue. The second and third sets were done afterwards at regular and slow speeds, respectively.

## 2.2 Theorem and governing equations

In order to analyze the joint forces of the upper extremity at the examined push-up speeds, we consider a three-joint multi-linkage system formed by the upper extremities (including hand, forearm, upper arm, and trunk). The free body diagram of each joint (wrist, elbow, and shoulder), joint forces and joint moments are shown in Fig. 2.

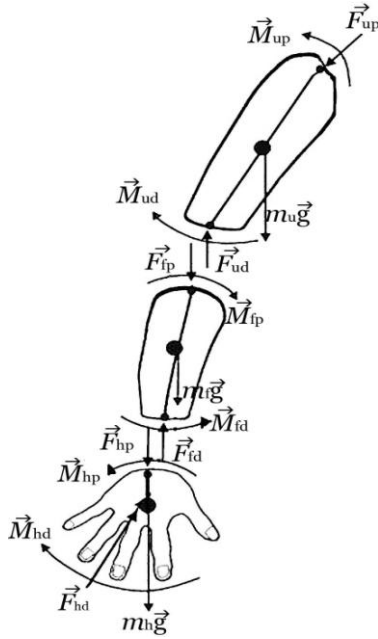


Figure 2. Segmental free-body diagram of upper extremity.

The governing equations for joint forces and joint moments are as follows:

From the free body diagram of the hand:

$$\vec{F}_{hp} = m_h \vec{a}_h - m_h \vec{g} - \vec{F}_{hd} \quad (1)$$

$$\vec{M}_{hp} = I_h \vec{a}_h - \vec{M}_{hd} - (\vec{r}_{hp} \times \vec{F}_{hp}) - (\vec{r}_{hd} \times \vec{F}_{hd}) + \vec{\omega}_h \times (I_h \cdot \vec{\omega}_h) \quad (2)$$

From the free body diagram of the forearm:

$$\vec{F}_{fd} = -\vec{F}_{hp} \quad (3)$$

$$\vec{M}_{fd} = -\vec{M}_{hp} \quad (4)$$

$$\vec{F}_{fp} = m_f \vec{a}_f - m_f \vec{g} - \vec{F}_{fd} \quad (5)$$

$$\vec{M}_{fp} = I_f \vec{a}_f - \vec{M}_{fd} - (\vec{r}_{fp} \times \vec{F}_{fp}) - (\vec{r}_{fd} \times \vec{F}_{fd}) + \vec{\omega}_f \times (I_f \cdot \vec{\omega}_f) \quad (6)$$

The symbols of the equilibrium equations are explained as follows. Where  $h$  = hand,  $f$  = forearm;  $\vec{F}_p$  is the proximal joint force;  $m\vec{a}$  is the effective force;  $m\vec{g}$  is the gravity force of the local segment;  $\vec{F}_d$  is the distal joint force;  $m$  is the mass of the segment;  $\vec{M}_p$  is the proximal joint moment;  $I$  is the mass moment of inertia;  $\vec{a}$  is the angular acceleration of the local segment;  $\vec{M}_d$  is the distal joint moment;  $\vec{r}_p$  is the rotation matrix of relative rotation between the proximal segment's local coordinates and the global coordinates;  $\vec{r}_d$  is the rotation matrix of relative rotation between the global coordinates and the distal segment's local coordinates;  $\vec{\omega}$  is the angular velocity of the local segment.

The kinematics and kinetics data were obtained experimentally. Based again on Newton's third law, the force and moment of a given joint will be of opposite sign when substituted into the equilibrium equation of the next body segment.  $m$  and  $I$  are a segment's mass and moment of inertia. The values of  $m$  and  $I$  are listed in Table 1 [17-18].

## 2.3 Data reduction

Laboratory-developed kinematics and kinetics software were used to calculate the joint angles, resultant forces and moments of the elbow [17,19-20]. A three-segment model, i.e., hand, forearm and upper-arm, was employed in the analysis. Each segment was assumed to be a rigid body. Eight CCD cameras were used to record the 3-dimensional positions of the markers. Three elbow joint angles, namely the hinge angle, rotational angle and horizontal deviation, were calculated using Euler's method with a y-x-z rotational sequence based on the attached markers [3,21]. A piezoelectric force plate was used to measure vertical and two shear forces as well as the location of

Table 1. Segmental mass and moment of inertia.

Upper-arm	Segmental mass (kg)	$1.07 \times dw \times (-2.14 \times Ht + 13.25 \times Wt + 76)$
	Moment of inertia ( $\text{kg} \cdot \text{m}^2$ )	
	backward - forward	$1.0e^{-7} \times (934 \times Ht + 1094 \times Wt - 224646)$
	medial-lateral	$1.0e^{-7} \times (627 \times Ht + 1304 \times Wt - 198020)$
	axial direction	$1.0e^{-7} \times (-338 \times Ht + 391 \times Wt - 19102)$
Forearm	Segmental mass (kg)	$1.13 \times dw \times (-2.06 \times Ht + 8.40 \times Wt + 369)$
	Moment of inertia ( $\text{kg} \cdot \text{m}^2$ )	
	backward - forward	$1.0e^{-7} \times (905 \times Ht + 537 \times Wt - 166237)$
	medial-lateral	$1.0e^{-7} \times (867 \times Ht + 566 \times Wt - 162961)$
	axial direction	$1.0e^{-7} \times (-142 \times Ht + 167 \times Wt - 9488)$
Hand	Segmental mass (kg)	$1.16 \times dw \times (1.69 \times Ht + 1.60 \times Wt - 62)$
	Moment of inertia ( $\text{kg} \cdot \text{m}^2$ )	
	backward - forward	$1.0e^{-7} \times (133 \times Ht + 48 \times Wt - 18865)$
	medial-lateral	$1.0e^{-7} \times (124 \times Ht + 34 \times Wt - 17258)$
	axial direction	$1.0e^{-7} \times (12 \times Ht + 26 \times Wt - 2404)$

dw: density of water ( $\text{kg}/\text{cm}^3$ ); Ht: subject's body height (cm); Wt: subject's body weight (pounds)

the center of pressure on the palm and the moment about the axis normal to the force plate during the push-up. Simultaneous measurement of the upper-extremity kinematics was obtained by motion analysis system. Segment mass and inertia data were estimated by anthropometry [18]. Angular velocity and acceleration were calculated with Euler parameter's method [19]. The force place loading equals the hand loading, with a reversed vector. The wrist loading is then calculated, using an inverse dynamic procedure with the Newton-Euler equations [17,19-21]. Then the loading of the elbow joints is determined.

A generalized cross-validation spline-smoothing (GCVSPL) routine at a cut-off frequency of 6 Hz was used for data-smoothing [22]. Joint angles, forces and moments of the elbow as functions of temporal percentile during push-up cycle were calculated and then used for analysis [22].

The raw EMG data were exported to Matlab (The Math Works, Inc., Natick, MA, USA) for signal analysis and processing. To compute a representative averaged amplitude over a period of time, the signal was rectified first, which involved converting negative voltages to positive voltages, then a linear envelope was used to estimate the volume of muscle activation [23-24], and EMG data were normalized by MVIC [25]. The new data for a subject performing MVIC were presented in terms of %MVIC. Finally, the muscle activation per unit time (MAPT) were defined as the area under the EMG curve during a chosen push-up cycle contained by the given cycle time, and it was given by the following formula:

$$\text{MAPT}\{EMG(t)\} = \frac{1}{T} \int_t^{t+T} \frac{EMG(t)}{MVIC} dt \times 100\% \quad (7)$$

MAPT represents the mean muscle accumulated activation, and the unit of MAPT during a single push-up cycle is %MVIC.

#### 2.4 Data analysis

The kinematic and kinetic data of the elbow between fast, regular and slow push-up speeds were analyzed statistically by repeated one-way ANOVA with  $p < 0.05$  as level of statistical significance. The independent variable was speed, and dependent variables were joint angle, resultant force, resultant moment and MAPT in data analysis. The post hoc analysis for the differences among the examined push-up speeds was done

with the help of the Bonferroni method. Elbow kinematics and kinetics at the three critical events in the push-up cycle were analyzed. The event of "Up" posture was defined as the initial posture with the elbow in full extension. The event of "Down" posture was defined when the chest was at the lowest position. The event of "Peak" value was defined when the kinematic or kinetic data were either maximal at the top of the curve or minimal at the bottom. Additionally, "descending" was defined as process from "Up" to "Down." "Ascending" was defined as process from "Down" to "Up."

### 3. Results

In the conditions of fast speed, regular speed and slow speed, the average times of the push-up cycle in each, respectively, were  $1.41 \pm 0.03$  s,  $2.01 \pm 0.08$  s and  $2.48 \pm 0.07$  s.

#### 3.1 Elbow joint angle

The means, standard deviations, and significant differences of elbow joint angles are listed in Table 2. In the frontal and sagittal planes, the elbow joint angles at three different push-up speeds at three critical events ("Up," "Down," and "Peak") of the push-up cycle were not significantly different. In the transverse plane, the elbow pronation angle at fast push-up speed was less than respective angles at regular and slow push-up speeds, but the differences were not statistically significant (Table 2).

#### 3.2 Elbow joint force

The pattern of anteroposterior (AP) shear force during a push-up was W-shaped curve with maximum AP shear force located at either side of the "Down" position. The AP shear force at the "Down" position for the fast push-up speed ( $-3.54 \pm 1.93\%$  BW) was significantly ( $p < 0.05$ ) greater than that for the slow push-up speed ( $-1.10 \pm 2.81\%$  BW). The peak posterior shear force for the fast push-up speed was also greater than forces for regular and slow push-up speeds, but there was no statistical significance (Table 3).

As for the AP shear forces, the mediolateral (ML) shear forces at regular and slow push-up speeds had a W-shaped

Table 2. Joint angles of elbow at the examined push-up speeds.

Push-up speed	Fast <sup>†</sup> (Mean (SD))	Regular <sup>‡</sup> (Mean (SD))	Slow <sup>‡</sup> (Mean (SD))	$p^{\S}$	Post hoc
Frontal Plane	Varus (+)	Valgus (-)			
Up	0.29 (0.35)	0.24 (0.14)	0.31 (0.40)	0.9070	
Down	16.06 (7.88)	16.26 (7.04)	18.24 (8.00)	0.7821	
Peak	16.06 (7.88)	16.26 (7.04)	18.24 (8.00)	0.7821	
Sagittal Plane	Flexion (+)	Extension (-)			
Up	10.28 (5.29)	8.37 (8.51)	10.01 (3.88)	0.7585	
Down	97.44 (13.45)	98.90 (9.15)	100.95 (15.79)	0.8346	
Peak	97.44 (13.45)	98.90 (9.15)	100.95 (15.79)	0.8346	
Transverse plane	Supination (+)	Pronation (-)			
Up	-72.57 (36.01)	-85.69 (8.75)	-85.12 (15.57)	0.3736	
Down	-27.97 (36.54)	-44.73 (16.46)	-37.36 (31.10)	0.4500	
Peak	-27.97 (36.54)	-44.73 (16.46)	-37.36 (31.10)	0.4500	

unit: degree

<sup>†</sup> F: fast push-up speed; <sup>‡</sup> R: regular push-up speed; <sup>‡</sup> S: slow push-up speed; <sup>§</sup> p value is significance of one-way ANOVA

Table 3. Joint forces of elbow at the examined push-up speeds.

Push-up speed	Fast <sup>†</sup> (Mean (SD))	Regular <sup>‡</sup> (Mean (SD))	Slow <sup>§</sup> (Mean (SD))	<i>p</i> <sup>§</sup>	Post hoc
Anterior/Posterior force	Anterior ( + )	Posterior ( - )			
Up	-0.11 (2.78)	3.58 (2.96)	1.62 (2.08)	0.004**	F-N
Down	-3.54 (1.93)	-1.94(2.98)	-1.10 (2.81)	0.0459*	F-S
Peak	-4.76 (2.02)	-3.82 (2.34)	-3.57 (3.70)	0.6073	
Peak position <sup>  </sup>	35% of PU cycle	32% of PU cycle	32% of PU cycle		
Lateral/ Medial force	Lateral ( + )	Medial ( - )			
Up	-1.86 (2.98)	-5.95 (3.65)	-1.84 (6.08)	0.0475*	F-R, R-S
Down	-18.67 (5.94)	-13.62 (3.66)	-13.07 (5.76)	0.0237*	F-R, F-S
Peak	-18.67 (5.94)	-15.44 (3.99)	-13.78 (5.59)	0.047*	F-S
Peak position	50% of PU cycle	69% of PU cycle	71% of PU cycle		
Axial force	Compression ( + )				
Up	20.73 (2.92)	27.74 (4.10)	29.026 (4.43)	0.0000***	F-R, F-S
Down	42.98 (6.24)	36.48 (5.00)	33.95 (4.59)	0.0008***	F-R, F-S
Peak	43.06 (6.51)	37.60 (5.04)	35.12 (4.75)	0.0032**	F-R, F-S
Peak position	51% of PU cycle	44% of PU cycle	42% of PU cycle		

unit: %body weight

<sup>†</sup>F: fast push-up speed; <sup>‡</sup>R: regular push-up speed; <sup>§</sup>S: slow push-up speed; <sup>||</sup> position of the peak force in percentage of push-up cycle (% of PU cycle)<sup>§</sup>p value is significance of one-way ANOVA. \**p*<0.05; \*\**p*<0.01; \*\*\**p*<0.001

Table 4. Joint moments of elbow at the examined push-up speeds.

Push-up speed	Fast <sup>†</sup> (Mean (SD))	Regular <sup>‡</sup> (Mean (SD))	Slow <sup>§</sup> (Mean (SD))	<i>p</i> <sup>§</sup>	Post hoc
Frontal Plane	Varus ( + )	Valgus ( - )			
Up	-0.76 (1.94)	-1.76 (3.63)	-1.28 (1.77)	0.7466	
Down	-2.24 (4.70)	-2.57 (3.72)	-3.12 (3.87)	0.9108	
Peak	-7.37 (2.08)	-4.46 (1.89)	-4.51 (3.14)	0.0403*	F-R,F-S
Peak position <sup>  </sup>	22% of PU cycle	22% of PU cycle	21% of PU cycle		
Sagittal Plane	Flexion ( + )	Extension ( - )			
Up	-0.12 (2.06)	-0.77 (1.91)	0.70 (2.55)	0.4208	
Down	-26.21 (7.21)	-20.27 (2.84)	-18.47 (4.30)	0.0165*	F-R,F-S
Peak	-27.57 (6.75)	-22.42 (4.29)	-20.55(4.99)	0.0464*	F-R,F-S
Peak position	36% of PU cycle	32% of PU cycle	34% of PU cycle		
Transverse plane	Supination ( + )	Pronation ( - )			
Up	-0.27 (0.26)	0.08 (0.49)	-0.15 (0.22)	0.1458	
Down	-2.18 (0.43)	-1.66 (0.67)	-1.38 (0.55)	0.0304*	F-S
Peak	-2.36 (0.33)	-1.92 (0.64)	-1.67 (0.36)	0.0219*	F-S
Peak position	73% of PU cycle	70% of PU cycle	72% of PU cycle		

unit: N m

<sup>†</sup>F: fast push-up speed; <sup>‡</sup>R: regular push-up speed; <sup>§</sup>S: slow push-up speed; <sup>||</sup> position of the peak force in percentage of push-up cycle (% of PU cycle)<sup>§</sup>p value is significance of one-way ANOVA. \**p*<0.05

curve. However, the ML shear force at fast push-up speed had a V-shaped curve with maximum medial shear force located at the “Down” event of push-up cycle. The ML shear force at the “Up” position for the regular push-up speed was 6% of body weight, and it was significantly ( $p < 0.05$ ) greater than forces at fast and slow speeds. There were group differences for the ML force at the “Down” position as a result of the different curves for different push-up speeds. The ML shear force at the fast push-up speed ( $-18.67 \pm 5.94\%$  BW) at the “Down” position was significantly ( $p < 0.05$ ) greater than forces at regular ( $-13.62 \pm 3.66\%$  BW) and slow push-up speeds ( $-13.07 \pm 5.76\%$  BW). In addition, the maximum medial shear force for the fast push-up speed ( $-18.67 \pm 5.94\%$  BW) was significantly ( $p < 0.05$ ) greater than that for the slow push-up speed ( $-13.78 \pm 5.59\%$  BW), as shown in Table 3.

The compressive axial (CA) force was greater than the AP and ML shear forces. In the axial force direction, the CA forces

at regular and slow push-up speeds had bimodal distributions, with there being two peaks on either side of a valley. In contrast, the maximum CA force for the fast push-up speed was at the “Down” position, in the middle of the push-up. The CA force at fast push-up speed was significantly greater than forces at regular and slow push-up speeds at the three critical events (“Up,” “Down,” and “Peak”) of the push-up cycle. The peak CA force at the fast push-up speed was 43.06% of body weight, which was 1.15 and 1.23 times greater than force for regular and slow push-up speeds, respectively (Table 3).

### 3.3 Elbow joint moment

The differences in the joint moments among the three push-up speed groups are listed in Table 4. The peak valgus moment at fast push-up speed ( $-7.37 \pm 2.08$  N·m) was significantly ( $p < 0.05$ ) greater than the peak valgus moment at

Table 5. The muscle activation per unit time (MAPT).

Push-up speed	Fast <sup>†</sup> (Mean (SD))	Regular <sup>†</sup> (Mean (SD))	Slow <sup>‡</sup> (Mean (SD))	<i>p</i> <sup>§</sup>	Post hoc
Supinator	26.94 (17.61)	33.23 (17.54)	40.52 (17.50)	0.241	
Pronator teres	25.04 (14.46)	29.34 (18.34)	34.27 (17.65)	0.483	
Triceps brachii	28.94 (9.82)	30.41 (6.28)	40.12 (10.07)	0.018*	F - S
Middle deltoid	24.38 (12.35)	28.62 (11.28)	32.78 (14.98)	0.364	
Biceps brachii	28.94 (15.13)	27.68 (9.79)	47.02 (16.92)	0.008**	F - S, R - S
Anterior deltoid	20.33 (11.88)	18.66 (7.82)	29.92 (15.79)	0.105	
Pectoralis major	24.33 (12.74)	30.15 (14.26)	33.91 (14.23)	0.308	
Posterior deltoid	16.13 (14.61)	27.16 (11.22)	32.02 (15.21)	0.045*	F - S

unit: %MVIC

<sup>†</sup>F: fast push-up speed; <sup>‡</sup>R: regular push-up speed; <sup>§</sup>S: slow push-up speed; <sup>§</sup>*p* value is significance of one-way ANOVA.\**p*<0.05; \*\**p*<0.01

regular push-up speed ( $-4.46 \pm 1.89$  N·m) and the peak valgus moment at slow push-up speed ( $-4.51 \pm 3.14$  N·m). In the fast push-up speed group, the peak extension moment was greatest ( $-27.57 \pm 6.75$  N·m) in the sagittal plane. The increase of pronation moment was significant at the “Down” and “Peak” events ( $p < 0.05$ ). The peak pronation moment was significantly ( $p < 0.05$ ) greater at the fast push-up speed ( $-2.36 \pm 0.33$  N·m).

### 3.4 Muscle activation

Differences in MAPT among the three push-up speed groups are listed in Table 5. There were significantly greater MAPT in the slow group. The effect was more prominent for the biceps brachii ( $p < 0.01$ ), triceps brachii and posterior deltoid muscles ( $p < 0.05$ ). The results showed that greater muscle activation occurred in the slow push-up speed group.

## 4. Discussion

Push-up exercise is a popular exercise commonly used in physical fitness and strengthening exercise programs. However, because of its significant demands on the body, it should not be done without knowledge of potential benefits and risks [26]. The exercise is used to train the upper extremities by use of actions that oppose the force of gravity, resisting the body's own tendency to fall to the ground. The trunk, shoulders, the elbows, hands and even the lower extremities must participate in the exercise. In addition to the help of bony articulation in resisting the external loading, the muscles and ligaments also play important roles as dynamic stabilizer and static constraint. Previous studies on push-up biomechanics have focused on the effect of the hand position or forearm posture on elbow joint loading [3,7-8,12]. The speed is an important variable in the experiment in terms of changing the movement accelerations during “descending” and “ascending” processes, with the result being that the elbow joint moves with different angular velocity and angular acceleration. However, there is little information regarding the relationship between the speed of the push-up exercise and elbow joint loading. In the present experiment, the relationship between the speed of the push-up exercise and elbow joint loading was investigated. Furthermore, the kinetics and kinematics of the elbow at three different push-up speeds were demonstrated.

The results showed that there were no statistically significant differences in the elbow joint angle among the three

push-up speed groups at the three critical events (“Up,” “Down,” and “Peak”) of the push-up cycle. These results showed that a standard push-up action was employed in all push-up experiments performed at different speeds.

Push-ups, bench pressing, and power lifting are common exercises for strengthening the upper extremity. However, soft-tissue injuries of the pectoralis major, subscapularis, and triceps have been reported in the literature [25,27-30]. These soft-tissue injuries usually result from eccentric contraction of the muscle in upper-extremity strengthening exercises. In Chapman's investigation, the fast-velocity lengthening contractions may induce greater muscle damage than slow-velocity contractions [14]. In the present study, significant increases in the posterior shearing force ( $p < 0.05$ ) and extension moment ( $p < 0.05$ ) to the elbow joint were observed in the fast push-up speed group. The joint force and moment represents the summation force and moment of the bone and corresponding soft tissues around the joint. This increase in elbow joint loading could increase the loading on triceps and further increase the chance of injury.

The ML shear force and the CA force of elbow joint were significantly affected by different push-up speeds (Table 3). In the fast push-up speed group, there were significant increases in medial shearing stress ( $p < 0.05$ ) and maximum valgus moment ( $p < 0.05$ ). Since the push-up is a repetition of flexion-extension motion, the speed variable affects the ML shear force. The ML shear force increased as the speed of the push-up experiment increased. Morrey et al. reported that the MCL is the major constraint for the elbow joint in resisting valgus stress and that the lateral collateral ligament (LCL) helps the elbow joint resist varus stress [9]. O'Driscoll et al. demonstrated that injury to the LCL and MCL can result in severe posterolateral instability of the elbow joint [6,10]. These increases in joint loading increase the risk of injury to the medial and lateral stabilizing structure of the elbow, putting the MCL, LCL, and flexor-pronator muscle group in jeopardy.

The supinator, pronator teres, triceps brachii, middle deltoid, biceps brachii, anterior deltoid, pectoralis major and posterior deltoid are major contributors during push-up. The muscle activations are generally affected by different push-up exercise variants or different hand positions [31-32]. Cogley et al. reported that the EMG activities of pectoralis major and triceps brachii muscle groups in a narrow base position were significantly ( $p < 0.05$ ) greater than in wide base position [31]. Gouvali and Boudolos found that the pectoralis major muscle

activation during the posterior push-up exercise variants was higher than normal, but triceps muscle activation was lower than normal [32]. In this study, the result showed that the muscle activations were significantly altered at different push-up speeds. Muscle activations were significantly larger during slow push-up experiment for triceps brachii ( $p < 0.05$ ), biceps brachii ( $p < 0.05$ ), and posterior deltoid muscle groups ( $p < 0.05$ ). Comparing the three push-up speed groups, it was found that performing the push-up experiment at slow push-up speed could lead to a significant decrease in elbow joint loading and elbow joint moment and further increase the muscle activation significantly. This may indicate that performing the push-up exercise at slow push-up speed is of greater benefit in muscle training.

## 5. Conclusions

In this study, the kinetics and kinematics of the elbow at three different push-up speeds were analyzed. The results showed that the elbow load and joint moment differed significantly among the three push-up speed experiments. The data obtained in this study not only describe the relationship between the load across the elbow joint and the push-up speed but also provide useful biomechanical information regarding to the strategy of performing push-up exercise. The peak axial forces and peak extension moments occurred near the "Down" position as the push-up speed increased. The peak elbow medial force and compression force at fast push-up speed were 1.35 and 1.23 times those at slow push-up speed, respectively. In addition, the peak valgus moment at fast push-up speed was 1.63 times that at slow push-up speed. The peak extension moment at fast push-up speed was 1.34 times significantly greater than that at slow push-up speed, and the pronation moment at fast push-up speed was 1.41 times significantly greater than that at slow push-up speed. The experiment results showed that the MAPT in biceps brachii, triceps brachii and posterior deltoid muscle at slow push-up speed was 1.62, 1.39 and 1.99 times the MAPT at fast push-up speed, respectively. These EMG data indicated that performing the push-up more slowly can increase the muscle activation significantly and thus have greater benefit in muscle training. In conclusion, performing push-up in slower speed may reduce elbow joint loading and increase muscle activation. Therefore, performing the push-up more slowly may be a better strategy for strengthening the upper extremities.

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