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Finger force vectors in multi-finger prehension

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Abstract

In a majority of studies on grasp, only normal forces were measured and only when a zero torque was exerted on a hand-held object. This study concerns finger force vectors during the torque production tasks. Subjects ($n = 8$) stabilized a handle with an attachment that allowed for change of external torque from -1.5 to 1.5 Nm. Forces and moments exerted by the digit tips on the object were recorded. At the large (>-0.375 Nm) supination torques the index/middle and ring/little pairs of fingers generated oppositely directed tangential forces. The index and middle finger produced forces in a downward direction and therefore did not support the load. At a zero torque and pronation torques, the middle, ring and little fingers produced forces along nearly the same direction. The vector of the index finger force was always directed differently from the vectors of other finger forces, the angles ranged from $19^{\circ}30'$ to $47^{\circ}40'$. The points of force application were systematically displaced with the torque, with the exception of the little finger. Tangential finger forces contributed substantially to the total torque exerted on the hand-held object.

Keywords

Finger forces; Prehension; Grasping

1. Introduction

Manipulation of a hand-held object requires humans to coordinate the forces produced by individual digits of the hand such that required net force and net torque are produced. What exactly people do when they exert both a torque and a force on a hand-held object remains largely unknown.

In a majority of publications on grasp, only normal forces were measured (e.g. Kinoshita et al., 1995, 1997; Li et al., 1998; Santello and Soechting, 2000; Zatsiorsky et al., 2002). However, in several recent studies, forces in three dimensions have also been analyzed (Burststedt et al., 1999, Flanagan et al., 1999; Baud-Bovy and Soechting, 2001). In these studies, subjects were required to lift an object from above by using three digits: the thumb, the index, and the middle or ring finger, while the torque equaled zero.

This study concerns with the digit force vectors during torque production tasks. Specifically, three hypotheses are addressed: (1) individual fingers exert forces in dissimilar directions, (2) the point of digit force application displaces systematically in various tasks and scales with the amount and direction of the generated torque and (3) tangential finger forces contribute to the torque production.

2. Methods

Eight right-handed healthy university students (four male, four female) served as subjects (age 27.6 ± 3.7 years, weight 68.6 ± 14.9 kg, height 1.76 ± 0.13 m). All subjects gave informed consent according to the procedures approved by the Office for Regulatory Compliance of The Pennsylvania State University.

Six-component force/moment transducers (four Nano-17 for the fingers, one Mini-40 for the thumb, ATI Industrial Automation, Garner, NC, USA) affixed to an ‘inverted-T’ handle were used for recording digit forces (Fig. 1). An eyehook used to suspend a weight hanger was located along the bottom edge of the horizontal beam. The position of the hook in the medio-lateral direction could be varied by sliding the hook in the slot that ran the width of the beam.

The thumb sensor was located at the midpoint of the handle. The center points of the index and middle fingers sensors were located 45.0 and 15.0 mm, respectively, above the center point of the thumb transducer. The center points of the ring and little finger sensors were located -15.0 and -45.0 mm, respectively, below the thumb transducer. The surfaces of the transducers were covered with 100-grit sandpaper. For different subjects, the static friction coefficient between the skin and sandpaper was in the range 1.4–1.5.

During the experiment, a 0.5-kg load was suspended from the beam at different positions with respect to the middle of the beam. Suspending the load at different positions caused torques of 0.375, 0.750, 1.125, and 1.500 Nm in both clockwise (CW) and counterclockwise (CCW) directions. The total mass of the apparatus with the load was 1.6 kg (weight 15.71 N). Subjects were instructed to take the handle from the rack, place the forearm on the table, and hold the handle statically in the air while maintaining the horizontal orientation of the level located on the top of the handle. Special attention was given to digit placement on the sensor such that the center of the digit surface coincided with the center of the sensor. The subjects were instructed to hold the handle “naturally with minimal force exertion”. When the subjects reported that they were holding the handle comfortably, data recording started. The analog signals were input to a 64-channel 12-bit analog-digital converter (PCI-6031, National Instrument, Austin, TX, USA). The digital signals were processed using a micro-computer (Gateway AMD800, North Sioux City, SD, USA). The sampling frequency was 50 Hz. The data were low-pass filtered with a second-order Butterworth filter at 5 Hz. The signals were recorded for 2 s. Each condition was repeated 10 times. The signals were set to zero before each trial. The order of the trials was pseudo-randomized. Breaks of at least 1-min were provided between trials to avoid fatigue.

Data acquisition software written in LabVIEW (National Instrument, NC, USA) was used to convert the digital signals into force and moment values. Data reduction was performed using Matlab (Mathworks, Inc., Natick, MA). Positions of the points of force application along axis Y with respect to the sensor center were solved as $y = M_Z/F_X$ where M_Z is the moment of force about axis Z and F_X is the normal force component. For each trial, the data were averaged over 1.8 s of the holding period (excluding 0.1 s at the beginning and at the end of the period). For each load position, 10 trials for each subject were averaged. The group averages were then computed. The cosines of the angles formed by the force vectors were computed using routine procedures of vector algebra. The Watson–Williams tests of circular statistics for two or several samples (Batschelet, 1981) at $\alpha = 0.05$ were used to compare the force direction among the subjects, fingers and tasks.

For the system to be at rest, the sum of all forces and moments acting on the handle should equal zero. Hence, assuming that the task is planar and the normal forces are sufficiently large to prevent slipping, the following three requirements should be satisfied:

1. The sum of the normal forces of the four fingers equals the normal force of the thumb.

$$F_{th}^n = F_i^n + F_m^n + F_r^n + F_l^n = \sum_{f=1}^4 F_f^n \quad (1)$$

2. The sum of the digit tangential forces equals the weight of the hand-held object.

$$L = F_{th}^t + F_i^t + F_m^t + F_r^t + F_l^t \quad (2)$$

3. The total moment produced by the digit forces about point o (see Fig. 1) is equal and opposite to the torque exerted on the object by external forces

$$T = \underbrace{F_{th}^n d_{th} + F_i^n d_i + F_m^n d_m + F_r^n d_r + F_l^n d_l}_{\text{Moment of the normal forces} \equiv T^n} + \underbrace{F_{th}^t r_{th} + F_i^t r_i + F_m^t r_m + F_r^t r_r + F_l^t r_l}_{\text{Moment of the tangential forces} \equiv T^t} \quad (3)$$

where the subscripts th, i, m, r and l refer to the thumb, index, middle, ring and little finger, respectively; the superscripts n and t stand for the normal and tangential force components, respectively; L is load (weight of the object), T is the external torque due to the suspended weight, and coefficients d and r stand for the moment arms of the normal and tangential force with respect to a pre-selected center, respectively. Note that $r_i = r_m = r_r = r_l = -r_{th}$. Also, normal forces can only push but not pull on the sensors ($F^n \geq 0$). Eqs. (1)–(3) impose three constraints on the 15 variables (finger force components and the vertical coordinates of the digit force application). Hence, the system has redundant degrees of freedom (DoF) that can be manipulated by the performer in different ways provided that constraints (1)–(3) are simultaneously satisfied.

3. Results

Digit forces changed both in magnitude and direction at different torques (Fig. 2). At the large (> -0.375 N m) supination torques, the index and middle finger produced forces in a downward direction and therefore did not support the load (Table 1). At these torques, the index/middle and ring/little pairs of fingers generated oppositely directed tangential forces. With the exception of the large (> -0.375 N m) supination efforts, the middle, ring and little fingers produced forces along nearly the same direction. According to the multi-sample Watson–Wilson test, the differences between the directions of the force vectors were statistically non-significant. At zero torque, the force vectors for the middle and ring finger were collinear, $\cos = 1.000$. The largest angle was between the index and little force vectors ($26^\circ 15'$, $\cos = 0.8967$). In all nine tasks, the index finger force direction differed significantly from the direction of the three other finger force vectors (27 two-sample Watson–Wilson tests). The cosine values ranged from 0.9421 (angle $19^\circ 30'$) to 0.6737 (angle $47^\circ 40'$).

Inter-subject variability significantly exceeded the intra-subject variability: for all 45 digit-torque combinations the F -value exceeded the critical value ($F(7, 72) = 3:30$ for $\alpha = 0:05$; the multi-sample Watson–Wilson test). Hence, statistically significant differences among the subjects in the individually preferred force directions have been observed.

The points of force application systematically displaced with the torque, with the exception of the little finger force (Fig. 3A). During supination efforts (negative torque direction) the point of application of the thumb force was displaced upward on average 9 ± 2 mm. A shift in the

opposite direction was observed in the finger forces, with the exception of the little finger. Hence, the locations of the digit forces depended on the torque direction and magnitude. The displacement of the digit force application resulted in a substantial increase of the moment arms of the normal finger forces d_f , and correspondingly the moments of the normal forces, especially during the supination efforts (Fig. 3B). The difference between the IMRL moment and the total moment of the normal digit forces (the SUM moment) in the figure is due to the displacement of the point of application of the thumb force during the supination efforts. During these efforts the SUM moment is almost twice the IMRL moment. Hence, the displacement of points of digit force application ('finger rolling') is functionally important: it changes the magnitude of the moment arms of the finger forces.

The moment of the normal finger forces comprised approximately 2/3 of the required total torque (Fig. 3B). The tangential force components contributed the rest. The thumb always exerted a tangential force in the upward direction and, hence, produced a negative (supination) moment. During the large supination efforts (-1.125 and -1.5Nm), the IMRL shear force also generated a supination moment. This was due to the downward action of the shear forces of the index and middle fingers.

4. Discussion

This is the first paper where force vectors acting at a digit-object surface during manipulative tasks requiring torque production have been recorded. For that reason, our opportunity to compare the present data with previously published results is limited. Santello and Soechting (2000) and Zatsiorsky et al. (2002) have investigated tasks similar to the one explored in this study. However, these previous studies only registered the normal finger forces (in the latter study the shear force of the thumb was also measured). In the study of Santello and Soechting (2000), the torques were small (below 0.375 N) and because of that the results are not immediately comparable. In Zatsiorsky et al.'s study, the torques were in the range of those used in the present experiment. There is a good correspondence between these two studies in the measured normal forces. The only difference was in the percent contribution of the moment of the normal forces into the total moment, 50% in the earlier study vs. about 67% in the present study. The difference may be due to the different finger positioning; the distance between the sensor centers was 30mm in this study and it was only 25mm in Zatsiorsky et al. (2002). The position of the fingers with respect to the thumb affects the moment arms and indirectly can affect the contribution of the normal and shear forces to the torque production.

The largest magnitude of the sine of the finger force vector with a horizontal line was 0.5793 (Table 1), which corresponds to an angle $35^\circ 20'$. For a friction coefficient $\mu = 1.4$ the slipping would occur if a finger force were directed at an angle $>55^\circ 30'$ to the horizon. The difference with the recorded angle was almost 20° . Hence, the slipping was not an issue in this experiment.

This study is limited to static analysis. The mechanisms of restoring equilibrium are not addressed. In particular, hand stabilization may be achieved by controlling mechanical impedance (Hogan, 1984, 1990). In future, constructing a grasp stiffness matrix and its partitioning into symmetric (conservative) and skew symmetric (nonconservative) components (Mussa-Ivaldi et al., 1985; Kao et al., 1997) can help in understanding the finger force patterns. Obtaining such a matrix via experiments requires perturbation of the grasp and is technically challenging.

In summary, at the large ($> -0.375\text{ N m}$) supination torques the index/middle and ring/little pairs of fingers generate oppositely directed tangential forces. In general, the direction of the index finger force vector differs from the direction of other finger forces. The digits, especially the thumb, roll on the contact surface thus changing the moment arms of the normal finger

forces. The tangential digit forces contribute substantially to the total torque production. The results of this study may serve as guidelines for constructing intelligent robot hands and hand prostheses.

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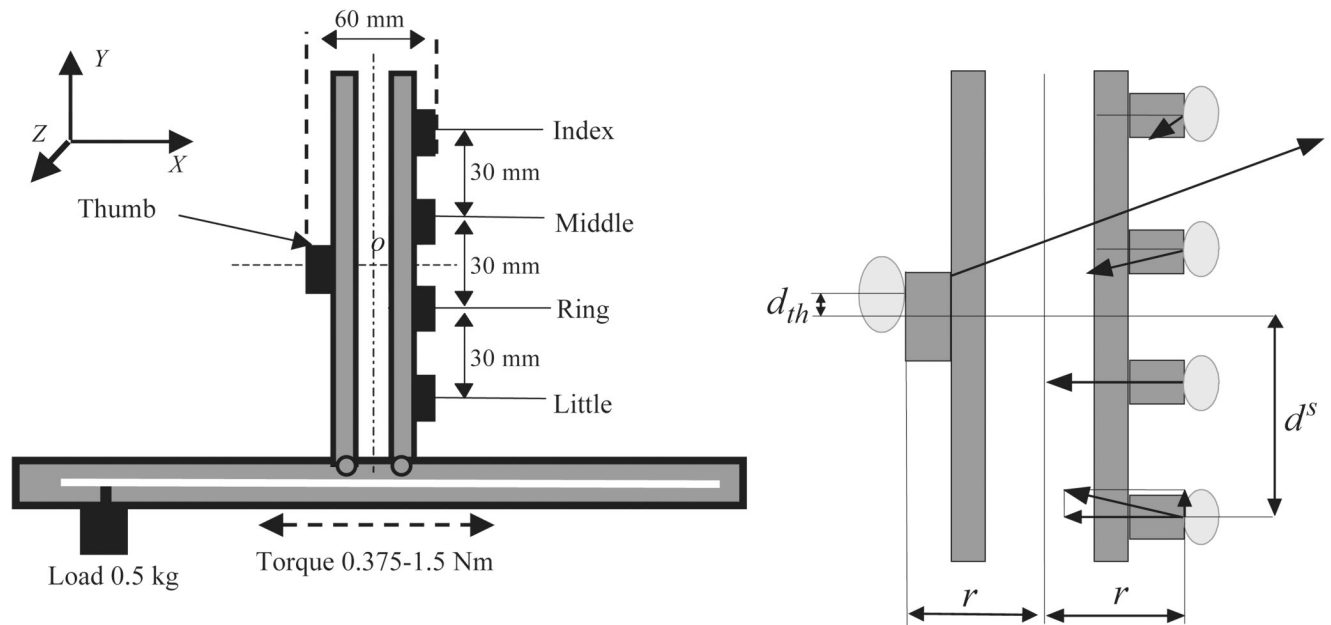


Fig. 1. Schematic drawing of the handle and an object-based system of coordinates (left panel) and the moment arms of the digit forces (right panel). Force components in the X direction are called the *normal forces*, in the Y direction—*tangential forces*. The magnitude of r is the same for all the digits. The sense of r 's is different for the thumb and finger forces. d^s is the projected distance from a center of the finger sensor to the center of the thumb center. d_{th} is the distance between the point of application of the thumb force and the center of the thumb sensor. The moment arm of the normal force of finger f with respect to the point of the thumb force exertion is $d_f = d_f^s + d_f^c - d_{th}$ where d_f^c is the distance between the point of application of the finger force and the center of the finger sensor (not shown in the figure). The figure is not to scale.

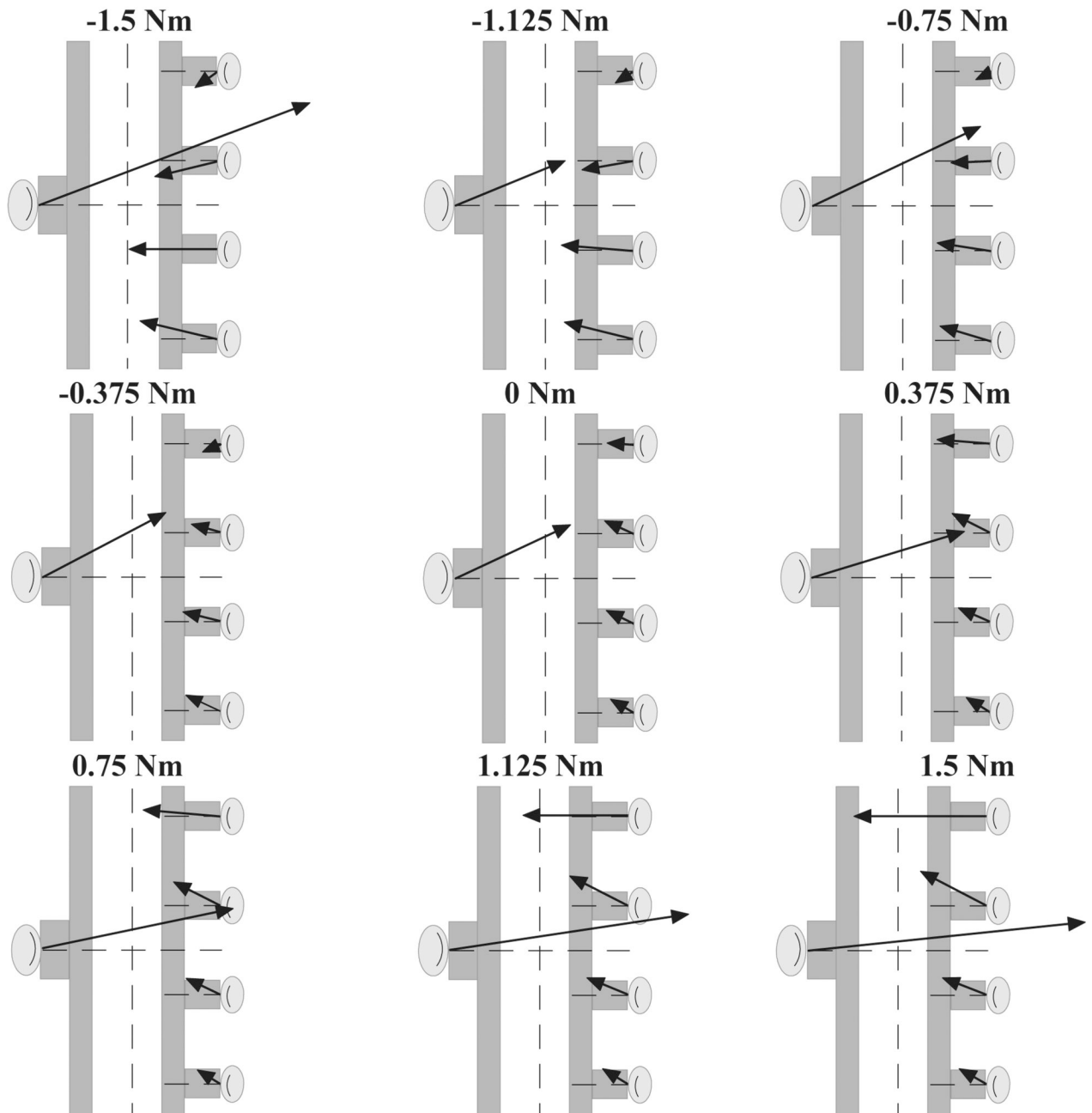


Fig. 2. Forces at the digit tips, group average. In this and the following figures, the positive and negative direction of the torque refers to the torque exerted by the subject (which is in the opposite direction to the torque due to the loading). Hence, the supination torque efforts are negative and the pronation torque efforts are positive. The origin of the object-fixed reference frame is at the interception of the vertical and horizontal dotted lines.

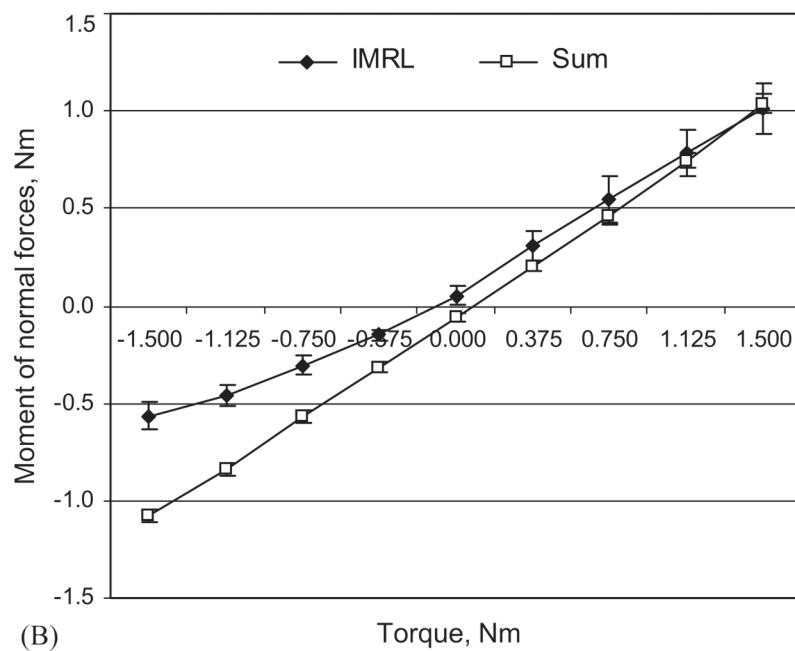
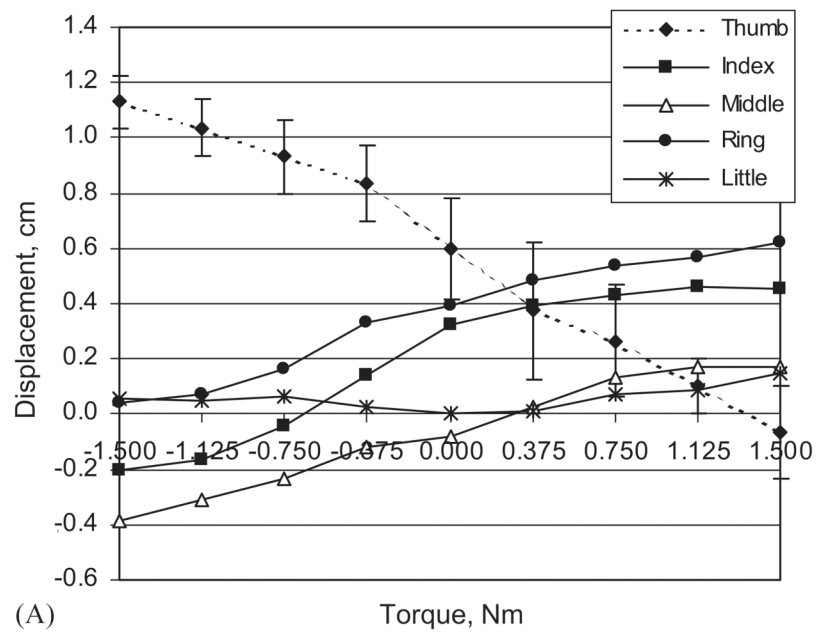


Fig. 3. Displacement of the point of application of digit forces in the vertical direction at the various torque levels (A) and its effect on the moment of the normal forces (B), group average and standard deviations. The abbreviation IMRL stands for total force/moment exerted by the index, middle, ring and little finger. The IMRL moments are computed with respect to the center of thumb sensor, while the SUM moments are computed with respect to the point of the thumb force exertion.

Table 1

Cosines of the angles formed by individual finger force vectors (the off-diagonal elements) and sines of the finger force vectors with a horizontal line (the elements on the main diagonal, in italics)

	I	M	R	L	I	M	R	L	I	M	R	L
I	-0.579(0.088)	0.930(0.056)	0.793(0.133)	0.674(0.102)	-0.535(0.110)	0.926(0.070)	0.801(0.142)	0.693(0.112)	-0.430(0.179)	0.919(0.124)	0.828(0.115)	0.741(0.133)
M		<i>-0.240(0.115)</i>	0.961(0.068)	0.898(0.068)		<i>-0.177(0.137)</i>	0.967(0.068)	0.916(0.079)		<i>-0.040(0.267)</i>	0.982(0.057)	0.946(0.088)
R			<i>0.037(0.130)</i>	0.984(0.018)			<i>0.079(0.139)</i>	0.987(0.022)			<i>0.149(0.092)</i>	0.990(0.014)
L				<i>0.212(0.075)</i>				<i>0.239(0.070)</i>				<i>0.288(0.061)</i>
	<i>-1.5Nm</i>				<i>-1.125Nm</i>				<i>-0.75Nm</i>			
I	-0.198(0.177)	0.893(0.112)	0.902(0.104)	0.806(0.126)	0.070(0.157)	0.935(0.071)	0.933(0.113)	0.897(0.108)	0.075(0.114)	0.921(0.053)	0.942(0.032)	0.886(0.065)
M		<i>0.264(0.226)</i>	0.999(0.035)	0.986(0.097)		<i>0.420(0.093)</i>	1.000(0.010)	0.995(0.006)		<i>0.457(0.063)</i>	0.998(0.014)	0.997(0.005)
R			<i>0.244(0.114)</i>	0.983(0.024)			<i>0.425(0.106)</i>	0.996(0.017)			<i>0.405(0.072)</i>	0.990(0.018)
L				<i>0.421(0.065)</i>				<i>0.504(0.083)</i>				<i>0.530(0.061)</i>
	<i>-0.375Nm</i>				<i>0Nm</i>				<i>0.375Nm</i>			
I	0.080(0.061)	0.923(0.036)	0.937(0.042)	0.891(0.044)	0.020(0.086)	0.899(0.053)	0.932(0.018)	0.861(0.058)	0.025(0.064)	0.897(0.048)	0.941(0.018)	0.876(0.037)
M		<i>0.457(0.060)</i>	0.999(0.012)	0.997(0.003)		<i>0.457(0.067)</i>	0.997(0.010)	0.997(0.006)		<i>0.464(0.059)</i>	0.994(0.014)	0.999(0.005)
R			<i>0.432(0.084)</i>	0.995(0.017)			<i>0.381(0.052)</i>	0.987(0.017)			<i>0.360(0.074)</i>	0.987(0.015)
L				<i>0.523(0.064)</i>				<i>0.525(0.081)</i>				<i>0.504(0.059)</i>
	<i>0.75Nm</i>				<i>1.125Nm</i>				<i>1.5Nm</i>			

Group average and standard deviations. A negative sine value signifies a downward force direction.