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Fast Adapting Mechanoreceptors are Important for Force Control in Precision Grip but not for Sensorimotor Memory

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ABSTRACT

Sensory feedback from cutaneous mechanoreceptors in the fingertips is important in effective object manipulation, allowing appropriate scaling of grip and load forces during precision grip. However the role of mechanoreceptor subtypes in these tasks remains incompletely understood. To address this issue, psychophysical tasks which may specifically assess function of type I fast adapting (FAI) and slowly adapting (SAI) mechanoreceptors were used with object manipulation experiments to examine the regulation of grip force control in an experimental model of graded reduction in tactile sensitivity (healthy volunteers wearing two layers of latex gloves). With gloves, tactile sensitivity decreased significantly from 1.9 ± 0.4μm to 12.3 ± 2.2μm in the Bumps task assessing function of FAI afferents, but not in a grating orientation task assessing SAI afferents (1.6±0.1mm to 1.8±0.2mm). Six axis force/torque sensors measured peak grip (PGF) and load forces (PLF) generated by the fingertips during a grip-lift task. With gloves there was a significant increase of PGF (14±6%), PLF (17±5%) and grip and load force rates (26±8%; 20±8%). A variable weight series task was used to examine sensorimotor memory. There was a 20% increase in PGF when the lift of a light object was preceded by a heavy relative to a light object. This relationship was not significantly altered when lifting with gloves, suggesting that the addition of gloves did not change sensorimotor memory effects. We conclude that FAI fibres may be important for the online force scaling but not for the build-up of a sensorimotor memory.

New & Noteworthy: This manuscript provides insights into the role of cutaneous feedback in object manipulation and precision grip. Force control during object manipulation relies on prior experience and anticipation as well as feedback from mechanosensitive afferents. Using a graded model of experimental tactile dysfunction, we have selectively reduced the sensitivity of FAI, but not SAI mechanoreceptors and demonstrate that impairment of FAI function leads to selective deficits of object manipulation whereas it does not perturb sensorimotor memory.

INTRODUCTION

Sensory feedback from cutaneous mechanoreceptors in the fingertips is critical in effective object manipulation (Johansson and Flanagan, 2009). Tactile afferents enable appropriate scaling and synchronous coupling of grip and load forces to prevent excessive force or conversely object slippage during precision grip (Johansson & Westling, 1984). However, control of grip and load forces also relies on anticipatory force predictions based on prior experience, with sensorimotor memories utilised to anticipate force requirements involved in predictable object interactions (Flanagan et al., 2001). There are four classes of mechanosensitive afferents in the hand, fast adapting (FA) and slowly adapting (SA) types I and II (Johansson and Flanagan, 2009). Fast adapting (FAI) and slowly adapting (SAI) type I mechanosensitive afferents are highly enriched in the fingertips (Johansson and Valbo, 1979), while FAII and SAII are found at a uniform but lower density (Johansson and Flanagan, 2009). Classically, FAI afferents are associated with perception of high frequency, dynamic events while SAI afferents are sensitive to low frequency skin deformation. FAII afferents detect transient events such as vibration and SAII afferents respond to stretching and may function as proprioceptors (Johansson and Flanagan, 2009). However, the relative contribution of sensory feedback via FAI and SAI mechanoreceptors to online force scaling and the build-up of a sensorimotor memory have remained incompletely understood.

Deficits in tactile feedback produce significant functional difficulties, demonstrated in patients with sensory neuropathies (Nowak and Hermsdörfer, 2004) or experimental reduction of tactile sensation in healthy volunteers by digital anaesthesia (Monzée et al., 2003; Nowak et al., 2001; Augurelle et al., 2003; Johansson et al., 1992). While neuropathy and digital anaesthesia underscore the importance of sensory feedback in force scaling and memory build-up, they lead to a non-selective degradation of sensory afferent outflow from the finger tip. In the present study, we studied the functional consequences following selective reduction of the sensitivity of mechanoreceptors, achieved via wearing two layers of latex gloves.

Psychophysical tasks have been developed which may provide a selective readout of FAI and SAI mechanoreceptor function. Spatial acuity can be determined by the grating orientation task which is encoded by the activity in SAI mechanoreceptors in primates (Johnson and Philips 1981; Philips and Johnson et al., 1981). By contrast, the detection of a small elevated dot on a smooth surface or bump-like stimulus as in braille is signalled by FAI mechanoreceptors (La Motte and Whitehouse, 1986) and can be assessed by the 'Bumps task' (Kennedy et al., 2011).

Examination of FAI and SAI firing activity during precision grip via microneurography has provided correlative evidence that both FAI and SAI afferents are important in grip control but that FAI fibres are chiefly responsible for controlling grip force scaling (Macefield et al., 1996). However, the potential contribution of FAI fibres to controlling grip force scaling has not been experimentally demonstrated. We examined the hypothesis that the potentially selective reduction of activity in one mechanoreceptor (FAI) pathway leads to an impairment of online force scaling but not sensorimotor memory.

METHODS

12 healthy volunteers were recruited (6 males and 6 females, age 32.7 ± 1.3 years; mean ± standard error of the mean). Ethics approval was obtained from the London City and East National Research Ethics Service Committee and participants provided written informed consent. The Edinburgh Handedness inventory (Oldfield, 1971) established all participants as right-handed. Participants completed all tasks with and without the addition of two pairs of surgical latex gloves appropriate for their hand size (0.27 mm thick, Biogel Surgeons Gloves, Mölnlycke Health Care, Göteborg, Sweden). Multiple sizes were available to ensure appropriate fit. Two layers of gloves were chosen in order to ensure that tactile sensitivity was significantly reduced, as prior studies have identified elevations in sensory thresholds with multiple layers of latex gloves (Shih et al., 2001). The order of

presentation was pseudo-randomised, so that half of the participants completed the tasks without gloves to begin with while the other half started with gloves on first.

Psychophysical and Behavioural Tasks

All psychophysical tests were undertaken on the distal phalanx of the right index finger. For two tests the finger was stabilised with adhesive putty to prevent movement.

Assessment of tactile spatial acuity was undertaken via the grating orientation task with plastic JVP domes (Stoelting Co., IL, USA) with groove widths varying from 0.35mm to 12mm and starting from the 0.5mm spacing. The grooved dome was pressed steadily against the index finger for 3 seconds, and the participants reported the orientation of the grooves (either parallel or perpendicular to the finger) without vision in a two alternative forced choice paradigm of 10 stimulus presentations each in a pseudorandom sequence. The threshold corresponding to 75% correct discrimination was determined via linear interpolation as described previously (Van Boven and Johnson, 1994).

Assessment of mechanical sensitivity was undertaken using calibrated monofilaments (Optihair 2; Marstock nervtest, Schriesheim, Germany) as in Rolke et al. (2006). Monofilaments ranged in a geometric order of 12 filaments between 0.25 and 512 mN. The method of limits was used to determine the detection threshold with a series of stimuli presented to participants with their eyes closed. The threshold was determined as the geometric mean of five pairs of 'up and down' stimuli presentations alternating from stimulus detection to failure of detection.

Assessment of tactile sensitivity was also undertaken using the 'Bumps' device (Kennedy et al., 2011) which consists of a checkerboard-like plate with a smooth surface divided into 12 squares. Each square contains 5 coloured circles of 4 mm diameter, with one randomly selected circle containing a single coin-shaped 550µM diameter bump of variable height. Bump height ranged from 26µm to 0.5µm over 4 plates. Participants were given standard instructions and asked to identify where the raised bump was located in each square, using their index fingertip to scan the plate. As per Kennedy et al., 2011, threshold was determined as the lowest height bump that could be correctly detected in a series of 3 consecutive correct detections, so that for a threshold of 2.5µm, bumps of 3µm and 3.5µm also had to be correctly identified. The lowest threshold was taken from two trials across all plates.

To assess functional ability and fine motor skills, two pegboard tasks were undertaken with the right hand. The average number of pegs inserted in 30 seconds across two trials was recorded for the Purdue pegboard (Lafayette Instrument Company, IN, USA; Tiffin and Asher, 1948). The number of seconds taken to insert 25 pegs into grooved slots was recorded for the Grooved pegboard (Lafayette Instrument Company, IN, USA).

Precision grip assessment

The tasks involved a precision grip with the thumb and index finger of a 225g manipulandum with two parallel smooth aluminium grip surfaces of 40mm diameter (Figure 1A). Six axis force torque sensors (Mini 40 F/T transducers: ATI Industrial Automation; North Carolina USA) were used to measure grip force (normal to the grip surface) and load force (tangential to the grip surface) as in Loh et al., 2010. Volunteers were seated with their right hand placed on a table. Talcum powder was applied to the fingers both with and without gloves to keep friction constant (Augurelle et al., 2003).

In the constant weight series, participants were cued to lift the manipulandum at a 5cm height and hold it for 5 seconds before replacing it on the table. A series of 20 trials was undertaken with an inter-trial interval of 7 seconds (end to onset). In the variable weight series, a pseudorandom sequence of weight changes of the manipulandum occurred. The manipulandum was coupled to a robotic arm (Phantom, Geomagic; as in Van Polanen and Davare, 2015) through a hole drilled through the table to enable hidden weight changes, as in Loh et al., 2010. The robot was programmed to provide a light or heavy resistance equivalent to 0.5 and 3 Newtons respectively in a pseudorandom order. Participants were cued to lift the manipulandum at a 5cm height and hold it for

2.5 seconds before replacing it on the table. 41 trials were undertaken (3.5 sec inter-trial interval; end to onset) so that there were 10 trials of each weight transition condition: light-after-light, heavy-after-light, light-after-heavy and heavy-after-heavy. To determine slip force and coefficient of friction, participants were asked to perform several trials lifting the manipulandum to a 5cm height and then slowly releasing grip to allow slip. For each condition, three trials were averaged, following completion of practice trials.

Data acquisition and analysis

Force data was digitized via a CED power 1401 interface and data were recorded in Spike 2 (Version 5.21, Cambridge Electronic Design, Cambridge UK). Analysis was done by custom-made scripts in Matlab (Mathworks, Massachusetts, USA) and variables measured for each trial included peak grip force (PGF), peak load force (PLF), static grip force, preloading phase duration (from onset of GF to onset of LF), loading phase duration (from onset of LF to lift-off of the object), maximum coefficient of correlation between LF and GF profiles from grip force onset ± 50ms, peak grip force (GF rate) and load force rates (LF rate) as the first derivatives of GF and LF (Figure 1, see also Davare et al., 2006). Slip force was measured as the minimal grip force to prevent slippage and determined as the grip force at the onset of slippage. Safety margin was determined as the excess static grip force above the slip force. The coefficient of friction was calculated as the slip force divided by the load force. To determine the coefficient of friction for the index finger, the slip force for the index finger was divided by half the load force at the onset of slippage, assuming that the index finger supported half of the load of the symmetrical manipulandum, as in Kinoshita (1999).

Data from the variable weight series was analysed as in Loh et al., 2010. To determine the effects of sensorimotor memory, two ratios were calculated. The effect of a preceding heavy object was determined by the ratio of GF rate of the light-after-heavy trials divided by the light-after-light trials. A ratio of greater than 1 indicates that GF rate for a light object increased in trials preceded by a lift of a heavy compared to a light object. The effect of a light object in the preceding lift was determined by the ratio of GF rate in heavy-after-light trials divided by the heavy-after-heavy trials. A ratio lower than 1 indicates a reduced GF rate of a heavy object with a preceding light object compared to a heavy one. Results were given as mean ± standard error of the mean and analysed with SPSS (Version 21, IBM) using paired t-tests and Pearson correlation coefficients as appropriate. A *p* value of less than or equal to 0.05 was considered significant.

RESULTS

Psychophysical tasks

Sensory thresholds were significantly increased in participants wearing gloves. Bumps detection threshold (no gloves 1.9 ± 0.4 µm; with gloves 12.3 ± 2.2 µm; $P<0.0005$) and monofilament detection threshold (no gloves 0.6 ± 0.07 mN; with gloves 6.4 ± 1.7 mN; $P\leq0.005$) were elevated (Figure 2A). However, there were no changes in the ability to undertake the grating orientation task with the addition of gloves (no gloves 1.6 ± 0.1 mm; with gloves 1.8 ± 0.2 mm; $P >0.2$; Figure 2B), suggesting that FAI but not SAI mechanoreceptor function was disrupted. In addition, gloves significantly reduced performance in both the Purdue pegboard (no gloves 17.0 ± 0.4 pegs in 30sec; with gloves 14.6 ± 0.4 pegs in 30sec; $P<0.005$) and the Grooved pegboard tasks (no gloves 52.9 ± 1.3 sec; with gloves 61.1 ± 2.2 sec; $P<0.005$), suggesting impairment in global manipulative tasks.

Precision grip: Constant weight series

A series of constant weight lifts was undertaken to test the effect of selective FAI impairment on the online force scaling within a trial. The addition of gloves increased grip forces, with peak grip force increased by 14 ± 6% and static grip force by 22 ± 6% (Table 1; Figure 3). Peak load force was also increased by 17± 5% with the addition of gloves. In addition both grip force rate and load force rate were enhanced, indicating that gloves produced a faster grip. GF rate was increased by 26 ± 8 % and

LF rate by 20 ± 8%. However, specific timing phases were not significantly affected by gloves (Preloading phase: no gloves 35.0 ± 5.7 ms; with gloves 42.6± 7.8ms P >0.2; Loading phase: no gloves 92.1 ± 9.5 ms; with gloves 105.0 ± 26.7 ms P >0.5) and the synchrony between grip and load forces was preserved (maximum correlation coefficient: no gloves 0.91 ± 0.01; with gloves 0.91 ± 0.02; P >0.5).

Precision grip: Variable weight series

A series of lifts of objects of variable weight was undertaken to examine the effect of selective FAI impairment on the trial-to-trial build up of sensorimotor memory. We quantified the anticipatory planning of fingertip forces based on the previous lift. There was a 20% increase in GF rate for light-after-heavy compared to light-after-light trials, indicating that the previous lift of a heavy object affected the GF rate. This is comparable to previous studies (Loh et al., 2010; Johansson and Westling, 1988). These values were unchanged by the addition of gloves, indicating that anticipatory planning of force was unaffected by the addition of gloves (GF rate ratios: no gloves 1.2 ± 0.03; with gloves 1.2 ± 0.04; P >0.2). Similarly, the GF rate for heavy-after-light trials was reduced by approximately 11% compared to heavy-after-heavy trials and there was no difference with the addition of gloves (GF rate ratios: no gloves 0.89 ± 0.02; with gloves 0.86 ± 0.03; P >0.2), indicating that the impairment of FAI mechanoreceptors did not disrupt grip force ratios with variable weights.

Slip force and safety margin

We controlled for friction by using talcum powder and confirmed that the addition of gloves decreased the coefficient of static friction by 33% as in prior studies (no gloves 0.27 ± 0.01; with gloves 0.21 ± 0.02; P<0.005). However, the friction range was similar between conditions (no gloves friction range 0.19 – 0.34; with gloves friction range 0.12 – 0.28). Slip force was increased by the addition of gloves (no gloves 3.6 ± 0.2 N; with gloves 4.7 ± 0.3 N; P<0.001). There was a trend towards increased safety margin but this was not significant (no gloves 5.0 ± 0.4 N; with gloves 5.7

± 0.7 N; P >0.05). The safety margin as a percentage of grip force also did not increase (no gloves 43 ± 2%; with gloves 47 ± 3%; P >0.2). To determine if changes in friction were partially responsible for the elevation of grip force, the extent of change in peak grip force was correlated with the extent of change in friction. While these variables were significantly correlated (correlation coefficient = 0.747; P<0.005; Figure 4), the direction of association (positive rather than negative correlation) was not consistent with a role of friction in driving an increase in grip force. Participants who experienced the greatest reduction in friction between bare hands to gloves had smaller (rather than larger) increases in grip force with the addition of gloves. There was no correlation between the peak grip force and friction values in either the gloves or no gloves conditions.

DISCUSSION

The present study utilised graded experimental tactile dysfunction to identify patterns in psychophysical and precision grip parameters associated with graduated sensation loss. Sensory thresholds were significantly elevated for tasks associated with FAI function but not for tasks relying on SAI mechanoreceptors. Accordingly, peak grip and load forces were elevated, as were maximum grip force and load force rates, but timing parameters were unaffected. In addition, there was no indication that the addition of gloves affected programming of fingertip forces based on the sensorimotor memory of the previous lift.

The role of mechanoreceptors in precision grip

Four types of mechanosensitive receptors have been identified in human glabrous skin, with the type I afferents - fast adapting (FAI) and slowly adapting (SAI) – present in high density in the fingertip (Johansson & Vallbo, 1979). The grating orientation task has been linked to SAI afferent activity, with strong responses to periodic gratings identified in monkey mechanoreceptive afferents (Johnson and Philips 1981; Philips and Johnson et al., 1981). Conversely, it has been demonstrated that the response to braille or bump-like stimuli is mediated by FAI afferents (La Motte and Whitehouse, 1986; Kennedy et al., 2011). In monkey mechanoreceptors, the number of FAI afferent impulses and the receptive field sizes of individual FAI afferents increased with bump height (LaMotte and Whitehouse, 1986). Similarly, in human fingertip skin biopsies, there was a correlation between Meissner corpuscle density and bump detection threshold (Kennedy et al., 2011).

In the present study there was a dissociation between psychophysical tasks. The bumps task was significantly impaired, while the grating orientation task was not affected, suggesting that the gloves may have selectively reduced FAI afferent activity. The bumps threshold has been demonstrated to be independent of pressure or velocity (LaMotte and Whitehouse, 1986). While physical cues to orientation may affect grating orientation threshold (Van Boven and Johnson, 1994), to reduce the risk of movement, the finger was immobilised with adhesive putty. There was a wider range in variability in bumps performance in participants wearing gloves than with bare hands, however, substantial variability in bump detection has also been identified in patients with sensory neuropathy (Kennedy et al., 2011), suggesting that there may be a range of responses to altered sensation.

Accurate force control during precision grip of objects with forefinger and thumb requires detailed information from mechanoreceptors. Microneurography of the median nerve during precision grip has demonstrated both FAI and SAI afferent activity in the initial response (Westling and Johansson, 1987). FAI afferents quickly adapt, but SAI afferents continued static discharge, and both afferent types burst when the object is released (Westling and Johansson, 1987). While both FAI and SAI afferents are involved in grip control, FAI afferents are primarily responsible for conveying information about object properties from initial contact (Johansson and Flanagan, 2009). In addition, FAI fibres convey information about coarse spatial features, responding to dynamic mechanical events, while SAI convey fine spatial detail and sensitivity to edge contours (Bensmaia et al., 2006). FAI afferents have a major role in scaling GF and LF during precision grip (Macefield et al., 1996) and have an important role in encoding friction (Johansson and Westling, 1987). While less densely innervated in the fingertip, FAII afferents signal at object lift off and set down during precision grip, while SAII encode the application of static forces during object lifting, although with less sensitivity (Johansson and Flanagan, 2009).

Results from the present study suggest the importance of FAI afferents in GF and LF scaling, which was disturbed by the addition of gloves. However microneurographic recordings would be necessary to confirm the role of FAI mechanoreceptors in precision grip and determine how partial reduction in tactile information affects different afferent subtypes. Further, traditional views of the complete segregation of mechanoreceptor afferents have been challenged and it is increasingly recognised that cortical integration is multimodal, involving inputs from multiple receptor types (Saal and Bensmaia, 2014). Accordingly the contributions of FAI and SAI afferents to grip control may overlap and involve complex interactions with other afferent subtypes (Johansson and Flanagan, 2009).

Experimental Modulation of Sensory Impairment

Digital anaesthesia has been utilised as an experimental model of tactile dysfunction, typically producing increased grip force and safety margin (Augurelle et al., 2002; Johansson et al., 1992; Nowak et al., 2003; Monzée et al., 2003). Temporal coupling of grip and load forces is typically preserved with anaesthesia (Augurelle et al., 2002; Nowak et al., 2003), although in some studies timing phases have been altered (Johnasson et al., 1992; Monzée et al., 2003). During digital anaesthesia, a higher safety margin was explained as due to a lack of cutaneous feedback to provide updates (Augurelle et al., 2002). In the present study, safety margin was not significantly increased, suggesting that the level of sensory impairment provided by the gloves was not sufficient to interfere with updating of sensorimotor memory.

Several studies have demonstrated the detrimental effects of gloves on manual dexterity (Dianat et al., 2012) and tactile sensation (Shih et al., 2001; Willms et al., 2009). Grip and load forces increase with increasing glove thickness (Kinoshita, 1999; Shih et al., 2001; Willms et al., 2009), although timing parameters were not affected, similar to the present study. The present results suggest that even partial reduction in sensation is sufficient to disturb the maintenance of appropriate GF level.

However, prior studies did not examine the impact on sensorimotor memory. In the present study, sensorimotor memory was assessed by comparing peak grip force rates between trials using different weights. Peak grip force rate occurs during the loading phase – prior to the onset of movement and before current trial information can be updated (Flanagan et al., 2001). Accordingly, the peak grip force rate is set without access to cues to object weight and by relying on information obtained from the previous lift (Flanagan et al., 2001). However, these ratios were unaffected by the addition of gloves, indicating that information about the weight of the object from the previous lift was fully available when wearing gloves, despite the modulation in grip force. Accordingly, the characteristics of the previous lift had an influence on subsequent lifts despite reduced sensation, suggesting that partial sensory feedback is sufficient to enable this effect. In contrast, grip force scaling due to sensorimotor memory can be disrupted by additional sensory inputs such as hand muscle vibration (Nowak et al., 2004), suggesting that sensory feedback disruption can influence sensorimotor memory in some settings.

While changes in friction were identified with gloves, these changes were not consistent with the effects of gloves on grip force, suggesting that gloves rather than friction were predominantly modulating grip force. Further, prior studies have demonstrated a disconnect between friction and grip force modulation, with altered coefficients of friction with gloves not solely responsible for changes in grip force (Willms et al., 2009). In addition, Kinoshita (1999) demonstrated increased friction with rubber gloves without talc, and also demonstrated increased grip force in this experimental setting. Shih et al. (2001) also identified tactile deficits, increased peak grip and load force and decreased coefficient of friction with gloves. However, while there was no difference between one, two and three layers of gloves in terms of friction, grip and load forces demonstrated successive changes, suggesting that altered friction was not directly responsible for changes. Interestingly, during digital anaesthesia the required adjustments of grip force to friction are disrupted (Augurelle et al., 2002), suggesting that cutaneous sensation is required for accurate assessment and reaction to frictional changes (Westling and Johansson, 1984). As mentioned previously, FAI function may be critical for accurate frictional assessment (Johansson and Westling, 1987; Cole et al., 1999), which may contribute to the discrepancy between grip force modulation and friction in the present study.

Conclusions

Identification of grip-lift profiles associated with different types of sensory dysfunction may assist in providing insights into the role of different subtypes of sensory neurons in object manipulation. While future studies should examine the impact of focal reduction in tactile sensitivity to avoid any effect of gloves on motor performance, the present results further characterise the components of sensorimotor loops involved in force control during skilled grasp. Specifically, our results suggest a potential role of FAI receptors for the online control of force but not for updating internal models about object weight. This model of graded tactile dysfunction may also provide insight into patterns of sensory dysfunction and their effect on precision grip in patient populations.

Abbreviations

GF	Grip force
LF	Load force
PGF	Peak grip force
PLF	Peak load force
FAI	Type 1 fast adapting mechanoreceptors
SAI	Type 1 slowly adapting mechanoreceptors

FIGURE LEGENDS

Figure 1 **A** Illustration of precision grip experiment, with the manipulandum and direction of grip and load forces shown. **B** Grip-lift profile demonstrating modulation in grip force (red) and load force (blue) over time, with the preloading phase marked between times 1 and 2 and the loading phase between times 2 and 3. **C** Cross-correlation coefficient between grip and load force profiles plotted against the time lag (ms) between grip and load force profiles. The plot demonstrates the maximum cross-correlation coefficient and the time lag at the maximum coefficient. **D** Grip force rate (red) and load force rate (blue) profiles, plotted as the first derivatives of grip and load force.

Figure 2 **A** Bumps task threshold (µm) for individual participants with and without gloves. **B** Grating orientation task threshold (mm) for individual participants with and without gloves. Mean ± SEM values for group data are shown with superimposed bar graphs.

Figure 3 **A** Grip force profile demonstrating changes (mean ± standard error of the mean) in grip force with the addition of gloves (upper curve) compared to bare hands (lower curve) in all participants. **B** Static grip force (N) for individual participants with and without gloves. Mean ± SEM values for group data are shown with superimposed bar graphs.

Figure 4 Correlation between change in peak grip force with gloves and changes in friction with gloves, demonstrating that participants displaying reduced friction with gloves also had smaller increases in grip force.

	No gloves (mean ± SEM)	Gloves (mean ± SEM)	P value
Peak Grip Force (N)	10.3 ± 0.8	11.5 ± 0.8	≤ 0.05
Peak Load Force (N)	1.6 ± 0.08	1.9 ± 0.1	≤ 0.005
Grip Force rate (N/s)	13.2 ± 1.9	15.7 ± 1.7	≤ 0.05
Load Force rate (N/s)	3.2 ± 0.2	3.8 ± 0.3	≤ 0.05
Static Load Force(N)	1.2 ± 0.07	1.3 ± 0.1	> 0.20
Static Grip Force (N)	8.6 ± 0.4	10.4 ± 0.7	≤ 0.01

TABLE 1 - Precision grip parameters

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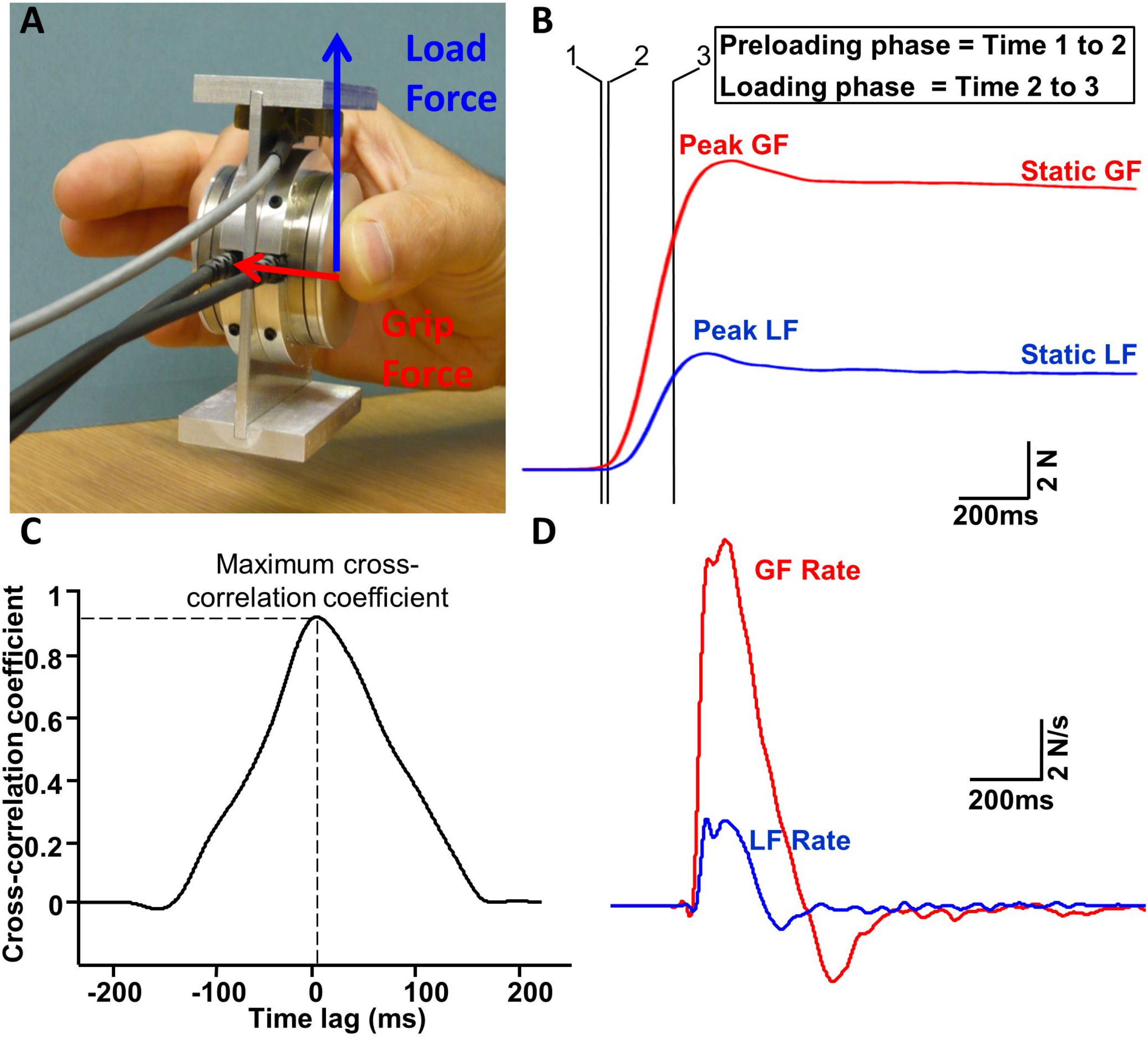
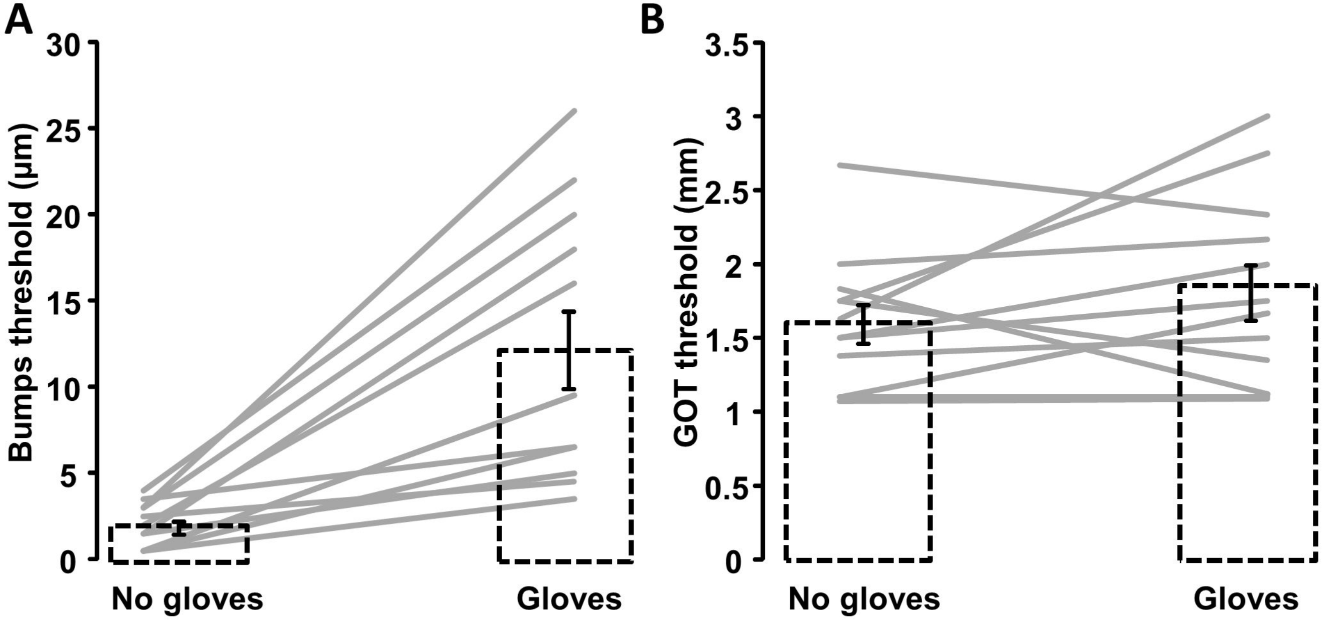
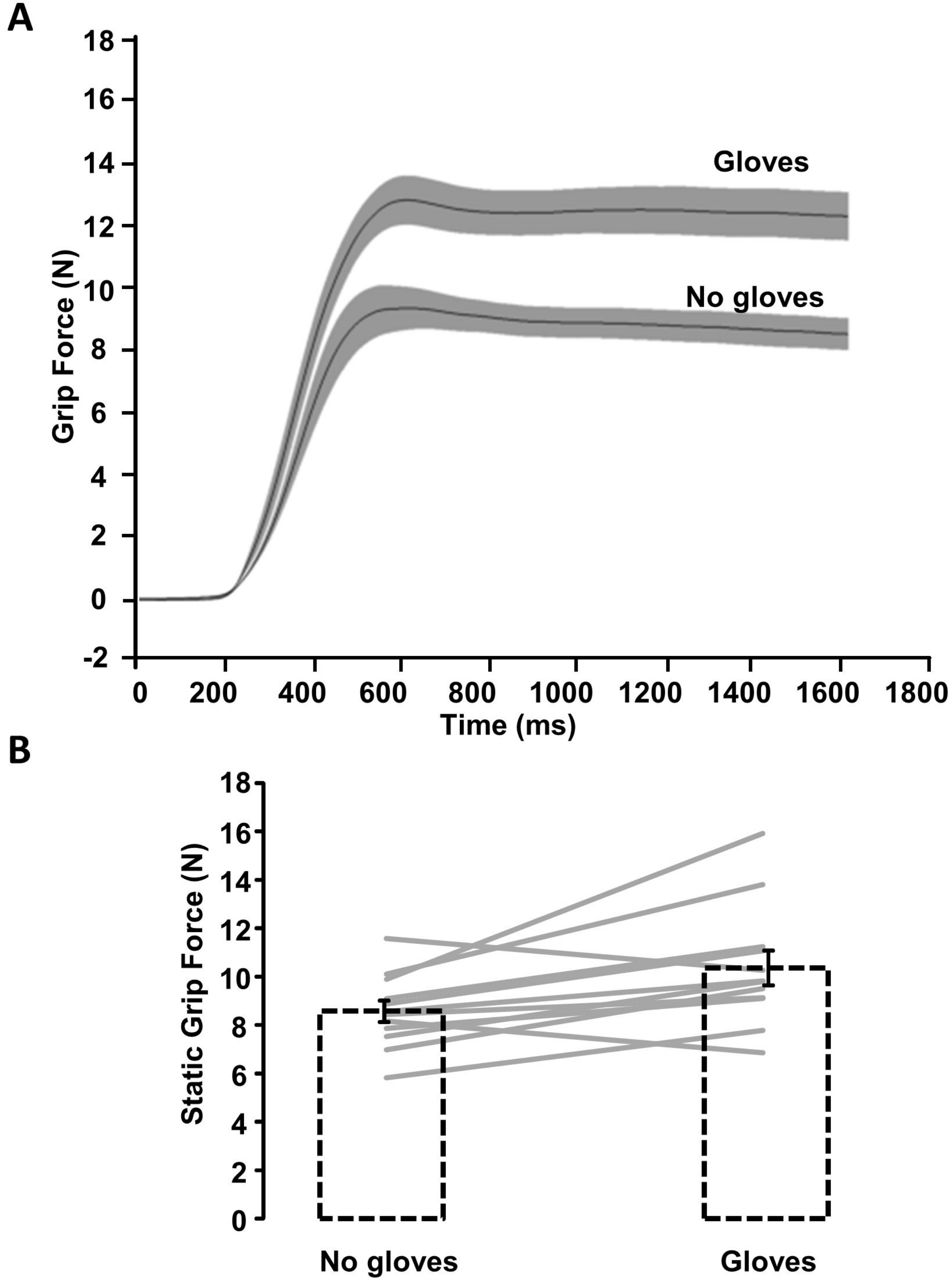
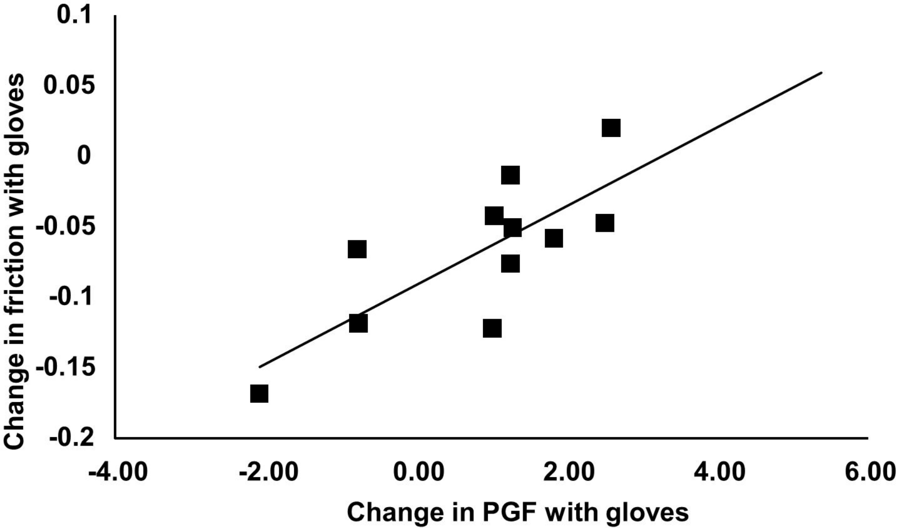

A
Load Force
Grip Force
B
1
2
3
Preloading phase = Time 1 to 2
Loading phase = Time 2 to 3
Peak GF
Static GF
Peak LF
Static LF
2 N
200ms
C
Maximum cross-correlation coefficient
Cross-correlation coefficient
1
0.8
0.6
0.4
0.2
0
-200
-100
0
100
200
Time lag (ms)
D
GF Rate
LF Rate
2 N/s
200ms


A
Bumps threshold (µm)
0
5
10
15
20
25
30
No gloves
Gloves
B
GOT threshold (mm)
0
0.5
1
1.5
2
2.5
3
3.5
No gloves
Gloves


A
Grip Force (N)
18
16
14
12
10
8
6
4
2
0
-2
Gloves
No gloves
0
200
400
600
800
1000
1200
1400
1600
1800
Time (ms)
B
Static Grip Force (N)
18
16
14
12
10
8
6
4
2
0
No gloves
Gloves


0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Change in friction with gloves
-4.00
-2.00
0.00
2.00
4.00
6.00
Change in PGF with gloves