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Radial force distribution changes associated with tangential force production in cylindrical grasping, and the importance of anatomical registration

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Abstract

Radial force (F_r) distributions describe grip force coordination about a cylindrical object. Recent studies have employed only explicit F_r tasks, and have not normalized for anatomical variance when considering F_r distributions. The goals of the present study were (i) to explore F_r during tangential force production tasks, and (ii) to examine the extent to which anatomical registration (i.e. spatial normalization of anatomically analogous structures) could improve signal detectability in F_r data. Twelve subjects grasped a vertically-oriented cylindrical handle (diameter = 6 cm) and matched target upward tangential forces of 10, 20, and 30 N. F_r data were measured using a flexible pressure mat with an angular resolution 4.8 deg, and were registered using piecewise-linear interpolation between five manually identified points-of-interest. Results indicate that F_r was primarily limited to three contact regions: the distal thumb, the distal fingers, and the fingers' metacarpal heads, and that, while increases in tangential force caused significant increases in F_r for these regions, they did not significantly affect the F_r distribution across the hand. Registration was found to substantially reduce between-subject variability, as indicated by both accentuated F_r trends, and amplification of the test statistic. These results imply that, while subjects focus F_r primarily on three anatomical regions during cylindrical grasp, inter-subject anatomical differences introduce a variability that, if not corrected for via registration, may compromise one's ability to draw anatomically relevant conclusions from grasping force data.

Keywords

grasp force coordination; hand and finger biomechanics; curve registration; statistical parametric mapping

1 Introduction

Prehension requires fine coordination amongst contact forces. During precision grip and pinch these forces are paramount, and a large body of literature exists regarding endpoint force coordination amongst the digits (reviewed in Zatsiorsky and Latash, 2008). Since these studies measure only endpoint forces they neglect pressure distributions across the hand, yet

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many grasping modes involve continuous contact across the palmar hand. For example: power grip to hold a tool handle, cylindrical grip to hold a glass of water, and spherical grip to hold a baseball. In these tasks endpoint forces cannot describe all mechanically-relevant contact information.

Consequently a variety of studies have explored contact force distribution, and the most widely studied model is cylindrical grasp (Gurram, R. et al., 1993; Shimojo, M. et al., 1995; Hall, C., 1997; Welcome, D. et al., 2004). As an aside we note that ‘cylindrical grasp’ is a type of ‘power grasp’, a grasping mode for which forces are distributed across the palmar surface of the hand; we presently use the term ‘cylindrical grasp’ to refer to power grasp of a cylindrical object. Cylindrical grasp studies reveal a non-uniform force distribution, with grip forces primarily focussed on the distal phalanges and metacarpal heads, but with non-negligible forces between these points as well (Kargov, A. et al., 2004). They also reveal that cylindrical grasp force distribution can be quite different from other power grasp modes (Wimer, B. et al., 2009), suggesting that cylindrical grasp is worthwhile, if not necessary to study in isolation.

We believe that there are three key issues which have not yet been explored in the cylindrical grasp literature. The first is tangential load. For many natural cylindrical grasp tasks, like holding a glass of liquid or handling a steering wheel, the tangential forces are the task-relevant forces while normal forces may be regarded as secondary, necessary primarily for slip prevention and sensory ending loading. While cylindrical grasp has been studied using explicit grasp force tasks, as well as pulling and pushing tasks (Welcome, D. et al., 2004), there are none, to our knowledge, that have investigated tangential force tasks.

The second and third issues we believe warrant further attention are anatomical normalization and continuous radial force distribution analysis. We use the term ‘radial force’ (F_r) to mean the component of force directed toward the cylinder’s central axis (Fig. 1); this force component is often referred to as ‘normal force’ in the literature, but we believe F_r more adequately distinguishes cylindrical grip from other grasping modes. For example: if an object, like a steering wheel, has a bump or dimple on its surface, normal forces will not necessarily be directed toward the object center, but F_r will. And by ‘anatomical normalization’ we mean accounting for anatomical differences amongst subjects. Presently we use a form of anatomical normalization known as ‘registration’ (Maintz, J. B. and Viergever, M. A., 1998; Sadeghi, H. et al., 2003; Kneip, A. et al., 2000) to align analogous structures within the continuous F_r distribution. We believe that continuous F_r characterization and previous forms of anatomical normalization represent two sides of the investigative coin: previous studies that have valued anatomical normalization sacrificed continuous F_r characterization, and studies that have valued the latter sacrificed the former. But we believe that, with registration, this sacrifice is not necessary. To explain:

Anatomical normalization has been implicitly adopted in studies which use individual sensors at pre-determined points on the palmar surface of the hand (Gurram, R. et al., 1993; Shimojo, M. et al., 1995; Hall, C., 1997; Welcome, D. et al., 2004; Pylatiuk, C. et al., 2006). However this measurement scheme constrains analyses to those particular points-of-interest, and thus cannot characterize the continuous F_r distribution in a completely objective manner.

Similarly, F_r distribution has been characterized using discrete sensors dispersed around the cylinder (Wimer, B. et al., 2009) or using finer pressure sensor arrays (Aldien, Y. et al., 2005; Lemerle, P. et al., 2007; Seo, N. J. et al., 2007; Young, J. G. et al., 2010), but in these studies the F_r data were described with respect to the handle rather than with respect to the

hand. This may be problematic in cases of non-negligible inter-subject hand size variation, where positions on the handle cannot be mapped directly to hand structures.

Registration overcomes these difficulties by transforming the F_r distribution to an anatomically normalized space. Some studies employed registration to study the F_r distribution (Aldien, Y. et al., 2005; Seo, N. J. et al., 2007), even using impressive 3D kinematic models to do so (Sinsel, E. W. et al., 2010), but these studies employed region-of-interest discretization, effectively breaking up the continuous F_r distribution into discrete, comparatively low-resolution chunks. This process effectively returns the data to the discrete domain, as if F_r had been measured with large discrete sensors. This is important because such discretization can corrupt the underlying data via regional conflation (Pataky, T. C. et al., 2008).

The purposes of this study were thus: (i) to describe how cylindrical grasp's radial contact forces are shared across the palmar surface of the hand during tangential force production, and (ii) to determine the extent to which registration can improve continuous F_r signal detection. Based on the literature we expected uniform F_r increases around the handle surface with increasing tangential load (Zatsiorsky, V. M. and Latash, M. L., 2008), that the greatest F_r would occur at the distal phalanges and metacarpal heads with negligible forces elsewhere (Hall, C., 1997; Kargov, A. et al., 2004), and that registration would reduce inter-subject F_r distribution variability (Sadeghi, H. et al., 2003), thereby improving the statistical detection of the aforementioned effects.

2 Methods

2.1 Subjects

Twelve right-handed male subjects participated in this study (age: 32 ± 8.1 years, height: 178.0 ± 6.6 cm, mass: 81.5 ± 14.8 kg, hand length: 18.6 ± 1.0 cm – from the proximal palmar crease to the tip of the third digit, hand width: 9.1 ± 0.6 cm – at the metacarpal heads). None reported neurological or upper extremity pathology, and each provided informed consent according to The Pennsylvania State University Institutional Review Board.

2.2 Equipment and experiment

Subjects were secured with two shoulder/waist straps to a height-adjustable chair so that their upper and lower arms were parallel to the horizontal plane and so that their shoulder and elbow angles in the horizontal plane were 0 and 90 deg, respectively (Fig.1). Subjects grasped a vertically-oriented cylindrical polyvinyl chloride (PVC) handle (diameter = 6 cm) just large enough to prevent finger-thumb touching around the handle. The handle base was fixed to a 6-axis load cell (Mini-85, ATI Industrial Automation, Apex, NC, USA) which was free to move in the xy plane via low-friction sliders. Force data were measured at 1000 Hz using LabView 8.2 (National Instruments, Austin, TX, USA).

A flexible pressure mat (PX200:100:100:10, XSENSOR Technology Corp., Calgary, Canada) was fixed to the PVC handle using overnight pre-dried adhesive spray (Photo Mount, 3M, St. Paul, MN, USA). While the adhesive supported the weight of the light mat, the mat's data cables were supported by cords, which were wrapped around steel ceiling rafters and then fastened to the mat edges and data cables using metal clips. The device (thickness: 2 mm, sensing area: 25×25 cm, resolution: 2.54 mm, 16 Hz) was manufacturer-calibrated to a range of 1-200 kPa.

The task was to produce an upward vertical force ($F_z = 10, 20, \text{ or } 30$ N) via bar-plot visual feedback. Three repetitions of each target F_z were conducted in a randomized order, yielding nine trials per subject. Data were collected for 5 s, including both force development and

steady-state about the target F_z . Subjects were instructed to maintain a constant grasping posture between trials (20 s). A foam-covered PVC half-pipe arm-rest was suspended from rafter cables; subjects were permitted to use this arm-rest only between trials.

2.3 Data processing

The time window between 2 and 4 s was selected for analyses; this window was verified to follow the initial F_z ramping period, and was cut short of the 5 s period to avoid anticipatory relaxation. Both the pressure data, originally in a 3D laboratory coordinate system (Fig.2), and the F_z data were averaged within these time windows. The averaged, unwrapped pressure images (Fig.3a), which were originally on a 100×100 grid, were manually cropped to a size of 52×75 (132×190 mm) to exclude pressure cells that were not under the hand. Five points of interest, to be used in subsequent analyses, were manually digitized on the cropped images: distal thumb phalanx - DP1, first and second metacarpophalangeal joints - MCP1, MCP2, distal phalanges of index and middle fingers - DP2, DP3.

Radial force (F_r) distributions (Fig.3b) were then computed by summing along the vertical (z) direction as follows:

$$F_r(\theta) = \frac{A}{\Delta r} \sum_{z=0}^Z I(\theta, z) \quad (1)$$

where θ is the polar angle (Fig.1b), A is the area of a single sensor (6.45 mm^2), Δr is the angular distance between pressure cells (0.083 rad), and $I(\theta, z)$ is the pressure recorded at the handle's (θ, z) coordinates. The resulting F_r distributions (Fig.3b) are 1D distributed loads (units: N/rad). Just as pressure (i.e. N/mm^2 , a 2D distributed load) is more informative than absolute force when using pressure measurement systems with arbitrary spatial resolution, the present units (N/rad) are more informative than absolute force units when measuring F_r with arbitrary angular resolution.

The data were then averaged within-subjects, separately for each F_z (10, 20, 30 N), yielding three F_r distributions per subject. The F_r data were analyzed as both distributed F_r (units: N/rad) and as 'force sharing' (units: % grip force), where we presently define 'grip force' as:

$$\text{grip force} \equiv \sum_{\theta=0}^{2\pi} F_r(\theta) \quad (2)$$

Anatomically analogous $F_r(\theta)$ features were initially unaligned (Fig.4a). To compensate we used a piecewise-linear spatial warping registration procedure (Kneip, A. et al., 2000) between the five manually digitized points of interest (Fig.3a). The result was improved analogous alignment (Fig.4b). Rather than directly analyzing registration effects via a comparison of pre- and post-registered (dis)similarity metrics like mean squared error, the effects of registration were presently examined indirectly, through separate statistical analyses of original and registered data. That is, we presently sought to examine only the extent to which registration amplified the ultimate statistical results.

2.4 Statistics

F_r distributions were analyzed using Statistical Parametric Mapping (SPM), a set of methods developed in the neuroimaging literature (Friston et al., 2007), but which have also been shown to be useful for a variety of smoothly varying biomechanics datasets (Pataky, 2010). Briefly, SPM uses random field theory (Adler, 1981) to search the entire lattice-sampled

measurement space for both the location and extent of experimentally-induced signals. After one computes a test statistic curve, for example as a set of t values at each point in the measurement space, a family-wise error-rate, usually 0.05, is used to determine a t threshold below which results are not considered significant. In this sense SPM is very much like traditional univariate or multivariate statistical testing. However, SPM's main difference is that, since the underlying data have spatial structure and are spatially smooth, values surviving the threshold tend to form connected clusters. It can be shown that statistical inference, or p -value computation, can be comprehensively conducted on cluster-specific metrics like cluster size and height (Adler, 1981). Just as in univariate testing precise p values depend on the experimental degrees of freedom, but for SPM analyses p values are also dependent on the underlying field smoothness, which can be estimated directly from the spatial derivatives of the statistical model residuals (Friston, K. J. et al., 2007).

Presently SPM was used to assess the linear relation between F_z and $F_r(\theta)$ using the regression model:

$$F_{ri}(\theta) = \beta(\theta)F_{zi} + \gamma(\theta) + \varepsilon_i(\theta) \quad (3)$$

where i indexes observations, β and γ are the regression slope and the intercept, respectively, and where ε_i is the residual of the i th observation. First, least-squares estimates of β were obtained separately for each subject. Next, in a second-level mixed-effects analysis the test statistic was computed as:

$$t(\theta) = \frac{\frac{1}{n} \sum_{j=1}^n \hat{\beta}_j(\theta)}{\frac{1}{\sqrt{n}} \hat{\sigma}(\theta)} \quad (4)$$

where n is the number of subjects, $\hat{\beta}_j$ is the estimated slope for subject j , and $\hat{\sigma}$ is the estimated standard deviation. Statistical inference was conducted using a family-wise error rate of $\alpha = 0.05$ and the radial extent of clusters that survived the corresponding $t(\theta)$ threshold (Friston, K. J. et al., 2007). General analyses were implemented in Python 2.7 using the Enthought Python Distribution 7.0 (Enthought Inc., Austin, TX, USA), and SPM analyses were conducted using SPM1D (Pataky, T. C., 2011).

3 Results

Irrespective of F_z , radial forces were primarily limited to three regions: MCP2, DP2, and DP1 (Fig.5a,b), and angular windows of 30 deg around these three regions accounted for a median 75.1% of the total grip force (range: 45.9% – 99.3%; across all subjects and conditions). F_r tended to increase with F_z (Fig.5a,b), and statistical analyses found this trend to reach significance (Fig.5c,d), especially at DP1, but also continuously along the handle surface from MCP2 to DP2.

The magnitude of the F_z -induced F_r increase was region-dependent (Fig.5b), partially because the three main contact points did not form an equilateral triangle and thus static equilibrium would not be maintained with equal force increases. All aforementioned F_r results were both qualitatively and statistically accentuated by registration, as indicated by t statistic amplification (Fig.5c,d).

Force sharing (Fig.6a,b) exhibited the opposite trend: F_r (% grip force) decreased with increased F_z , implying that F_r was spread over a larger contact area, likely via increased tissue deformation. Despite these trends, and while the distal portion of the fingers' distal

phalanges approached the threshold for significance (Fig.6d), ANOVA found no differences amongst the three F_z conditions ($p > 0.05$). We note that, like a typical univariate case, the present ANOVA yields a critical F threshold based on the *a priori* Type I error rate of $\alpha = 0.05$, and F values below this threshold are deemed non-significant. We finally note that, like the absolute F_r results, registration accentuated the F_r sharing trends, as indicated by F statistic amplification (Fig.6c,d).

4 Discussion

4.1 Hand coordination

The present findings of distally focussed forces agrees with many previous studies on maximal grasp (Gurram, R. et al., 1993; Shimojo, M. et al., 1995; Wimer, B. et al., 2009; Hall, C., 1997; Lemerle, P. et al., 2007; Sinsel, E. W. et al., 2010). That distal force concentration is consistent for sub-maximal and maximal tasks suggests that the distal phalanges are likely the most important effector for F_r production. The present basic force distribution (DP1, DP2-3, MCP) has also been reported elsewhere (Gurram, R. et al., 1993; Hall, C., 1997), but the angular F_r distribution, and specifically the isolation to these three regions has not been shown as clearly before, due mainly to previously insufficient angular resolution.

One study (Pylatiuk, C. et al., 2006) reported distally concentrated forces (37%), but also found reasonably high forces at the middle (25%) and proximal (12%) phalanges. Another (Enders, L. H. and Seo, N. J., 2011) reported similar percentages: 47%, 25%, and 28%, respectively. While the present results showed very little force sharing by the middle and proximal phalanges (Fig.6), the differences between the present and former studies may partially be explained by small tangential forces; Pylatiuk et al. (2006) required a total vertical force of only 5-10 N. Differences between the present and latter studies may be partially explained by hand dominance and task constraints; Enders and Seo (2011) measured the non-dominant hand and placed a single sensor under only one phalanx segment at a time, potentially creating a segment-specific task perception. Regardless, the present study also found systematic F_r increases with F_z along the lumped finger segment from MCP2 to DP2 (Fig.5d). Thus, while forces are almost certainly concentrated distally, it is also apparent that more proximal portions of the finger phalanges contribute to the mechanical task in a non-trivial manner.

Finally, since F_r did not increase equally at all contact points (Fig.5b,d), we can infer that the hand did not behave in a clamp-like manner. That is, the hand did not simply squeeze the handle more tightly. Rather, grasp forces were increased in a coordinated manner.

4.2 Statistical parametric mapping (SPM)

We presently used SPM to analyze F_r distributions. In the present context SPM's main advantage was its anatomical detail, with statistical results having the same angular resolution as the original dataset. This is in contrast to previous studies, which either measured F_r distributions at low angular resolution (e.g. Wimer, B. et al.; 2009), or analyzed higher-resolution data with gross regionalization schemes (e.g. Aldien, Y. et al.; 2005). The importance of analysis resolution is echoed by Young et al. (2010), who wrote (p.1159): "*When the surface of the handle is lumped into 5 equal zones, the observed (force) trend is lost.*" Since analysis resolution can affect biomechanical conclusions, we would submit that SPM, or another similar method, is needed for maximum objectivity.

4.3 Registration

Failing to register data is double-edged: the higher inter-subject variability in non-registered data (Fig.4) at once reduces the t signal magnitude (Fig.5) and raises the critical t threshold. The latter occurs because SPM-based statistical inference depends on the underlying field smoothness (Friston, K. J. et al., 2007); when the underlying field is rough one is more likely to observe high t values simply by chance. In plainer terms, the sensitivity with which one can detect signals is directly related to registration.

While we currently employed a simple, manual, piecewise registration procedure (Kneip, A. et al., 2000), we note that there have been considerably more sophisticated methods employed in the hand pressure literature. In particular, Buczek et al. (2011) used cone frustra to model finger kinematics, and then to fit this model to observed hand pressure distributions (Sinsel, E. W. et al., 2010). Such techniques would likely be helpful to increase registration objectivity, and are likely necessary to objectively study 2D pressure distributions.

4.4 Limitations

Although we recorded 2D surface pressures (Fig.3a,b), we presently analyzed only F_r . This was done primarily to make the present data comparable to previous studies which either report polar force distributions (Pylatiuk, C. et al., 2006; Wimer, B. et al., 2009; Young, J. G. et al., 2010), or which report radial forces measured at arbitrary angular resolution. We presently preferred to focus on F_r in interest of simplicity, as only F_r data were necessary to emphasize registration's importance to cylindrical grasp analyses. We intend to explore the F_z distributions and 2D pressure data in future work.

It has been shown that many factors such as handle diameter (Seo, N. J. et al., 2007) and surface properties (Enders, L. H. and Seo, N. J., 2011) can affect F_r coordination. We presently did not consider these factors, again in interest of a simpler message regarding registration.

Finally, since we measured only pressures, we were unable to determine potential effects of local shear. It has been shown, for example, that radial forces are not typically balanced during power grip, that local shear forces are necessary for xy planar equilibrium (see Fig.1) (Wimer, B. et al., 2009). Local shears are clearly important for gaining a more complete perspective of the hand's management of quasi-static equilibrium.

4.5 Summary

This study examined radial force (F_r) distributions during cylindrical grasping while subjects produced tangential force. The main findings were that: (i) F_r increased significantly with tangential forces, but only at the distal thumb and along the lateral digits, not between the distal thumb and the fingers' metacarpal heads, (ii) F_r was concentrated primarily on the distal phalanges and the fingers' metacarpal heads, and (iii) anatomical registration qualitatively and statistically accentuated all trends. We presently argue that anatomical registration is necessary for maximum objectivity, and that continuous analysis of force distributions is necessary for maximum anatomical clarity.

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Figure 1. Experimental apparatus. (a) Side view. (b) Top view, with an exploded handle view indicating the polar coordinate system. The task was to produce tangential force in the upward (+z) direction.

Figure 2.
Example data, laboratory coordinate system. The thick line indicates the radial datum.

Figure 3.

Data processing overview. (a) Flattened raw two-dimensional data, view from outside the handle. (b) Polar force distribution, top view. Five points of interest were digitized: distal thumb phalanx - DP1, first and second metacarpophalangeal joints - MCP1, MCP2, distal phalanges of index and middle fingers - DP2, DP3.

Figure 4.

Radial force distributions for the $F_z = 30$ N task, (a) before, and (b) after registration. Gray and black curves depict within- and between-subject means, respectively.

Figure 5. Statistical results, comparison of original (left panels) and registered data sets (right panels). (a,b) Mean inter-subject F_r distributions and standard deviation clouds for each of the three F_z loading conditions. (c,d) $SPM\{t\}$ depicting the linear relation between F_z and F_r . The critical t value (at $\alpha = 0.05$) is depicted as a dark ring. The p values indicate the probability with which a supra-threshold cluster of the same radial extent as the given cluster is expected to occur by chance. A radial scale of {0,12} is maintained in panels (c) and (d) as very large t values are not as interesting as the t values near the critical t value.

Figure 6. Statistical results, comparison of original and registered data sets (left and right panels, respectively). (a,b) Mean F_r sharing distributions as a percentage of grip force, with standard deviation clouds. (c,d) SPM{F} depicting changes in F_r sharing across the three loading conditions. The critical F value (at $\alpha = 0.05$) is depicted as a dark ring. That SPM{F} did not reach $F_{critical}$ implies that F_r sharing did not change significantly across the loading conditions.