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Stiffness map of the grasping contact areas of the human hand

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Abstract

The elasticity and damping of the soft tissues of the hand contribute to dexterity while grasping and also help to stabilise the objects in manipulation tasks. Although some previous works have studied the force-displacement response of the fingertips, the responses in all other regions of the hand that usually participate in grasping have not been analysed to date. In this work we performed experimental measurements in 20 subjects to obtain a stiffness map of the different grasping contact areas of the human hand. A force-displacement apparatus was used to simultaneously measure force and displacement at 39 different points on the hand at six levels of force ranging from 1 N to 6 N. A non-linear force-displacement response was found for all points, with stiffness increasing with the amount of force applied. Mean stiffness for the different points and force levels was within the range from 0.2 N/mm to 7.7 N/mm. However, the stiffness range and variation with level of force were found to be different from point to point. A total of 13 regions with similar stiffness behaviours were identified. The stiffness in the fingertips increased linearly with the amount of force applied, while in the palm it remained more constant for the range of forces considered. It is hypothesised that the differences in the stiffness behaviour from one region to another allow these regions to play different roles during grasping.

1. Introduction

The hand is the end effector for humans, responsible for all the manipulation tasks usually carried out in daily life. It is composed of hard tissues (bones, joints) and soft tissues (skin, muscles, tendons, ligaments, nerves, blood vessels). The high elasticity and damping of the different soft tissues of the hand contribute to a cushioning effect, helping in both fine and gross manipulation tasks. Consequently, the human hand does not have contact stability problems due to its inherent compliance, in contrast to robotic hands (Weir, 2004). Friction between the hand and the object being manipulated plays also an important role in grasping. The normal forces in the contact area generate frictional tangential forces and torques, helping to immobilise the grasped object (Sancho-Bru et al, 2011).

Small or light objects are usually manipulated with the tips of the fingers and thumb, using what is called a precision grip, with emphasis on dexterity. Precision grip is primarily performed with a pulp pinch. However, some precision grips also use the lateral aspects of the thumb and index finger, as for example the key pinch. In contrast, greater or heavier objects are manipulated with a power grasp, involving the palm and palmar aspect of the fingers, with emphasis on security or stability (Cutkosky and Howe, 1990). The anatomy of the hand is adapted to this ambivalence, with higher touch sensitivity in the fingertips than in other parts of the hand (Schlereth et al., 2001). In this sense, the literature also contains several works aimed at developing mechanical models of the fingertip in order to investigate the mechanistic bases of touch (Dandekar et al., 2003; Gulati and Srinivasan, 1995; Serina et al., 1997; Serina et al., 1998; Srinivasan and Dandekar, 1996). These works showed that the relationship between force and displacement (stiffness) in the fingertip is non-linear and viscoelastic, and reveal an increment in stiffness with deformation (Gulati and Srinivasan, 1995; Serina et al., 1997). Furthermore, loading angle, loading rate and indentor contact area were observed to have an effect on this relationship, while fingertip dimensions, gender and subject age had little influence.

To our knowledge no previous experimental work has reported on stiffness in the different zones of the grasping contact regions of the human hand, which may have important implications in grasping analysis and simulation. Considering the differences in touch sensitivity among the different hand regions, we should expect a different force-displacement response between the fingertip and other areas of the hand, such as the finger joint creases or the centre of the palm. However, this aspect has not been confirmed by any previous research. A recent work has reported significant differences in stiffness depending on skin site in the arm and hand (Sandford et al., 2013), but only one of the five skin sites tested was relevant for grasping tasks, the thenar eminence.

The quantification of local stiffness throughout the contacting areas of the hand could be useful for different purposes. The data can be used in the simulation of human grasping (Sancho-Bru, 2011), where accurate modelling of the contact between the hand and the object during grasping is required, and it is essential to know the force-displacement response of the fingers and the palm of the hand. Fingertip data have already been used in an attempt to develop a model for estimating the fingertip forces in finger-tapping movements, which was applied as a new index for assessing neurological disorders such as Parkinson's disease (Shima et al., 2009). The data are also important for a proper compliant design of hand prostheses, in order to avoid stability problems (Weir, 2004). Moreover, this information could be of interest for the design of hand-held tools, as in hand vibration transmission (Dong et al., 2005). Finally, knowledge of the normal stiffness of soft tissues in the different parts of the hand of healthy individuals could be used to distinguish between normal and pathological tissue functioning. Dermatologists often use the sense of touch to assess skin properties. However, objective and quantitative measurements are essential to compare studies performed by different experimenters in different centres (Boyer et al., 2009).

The aim of the present work is to obtain the *in vivo* force-displacement response in the different hand regions that may come into contact with objects when grasping.

2. Materials and Methods

Twenty volunteer subjects, 10 men and 10 women, were selected for the experiment, most of whom were students (16) and, the others, university staff (4). Descriptive statistics of the subjects are shown in Table 1. All the subjects except one man were right-handed and none of them reported any previous hand pathologies. The dominant hand was used for the measurements. All the subjects gave their informed consent to participate in the experiment.

Thirty-nine points on the hand (Figure 1) were selected, representing the hand areas that most usually contact with objects when grasping. Points 1 to 30 and 39 were located on the volar surface of the fingers or the palm. They were selected to include representative points in segments and joints of all fingers and thumb, and also a selection of points in the palm where greater pressures and forces are present in cylindrical and power grasps (Pataky et al., 2012, Kargov et al., 2004). Points 31 to 38 were located on the radial side of the index finger or the ulnar aspect of the thumb. These areas participate partially in cylindrical grasps and in lateral pinches. First, the points were marked on the subject's hand and a photograph was taken as a reference for subsequent repetitions of the experiment, in order to improve repeatability. Care was taken in the order of measurements of the 39 points to avoid consecutive measurement of two points of the same proximal-to-distal ray, so as to allow normal blood flow to be restored in the area before starting measurement on a point.

A force-displacement apparatus (Mecmesin AFG500N) was used to register the data. The device is composed of a digital dynamometer for force measurement connected to a digital rule for displacement measurement. The accuracy of the dynamometer is 0.1% of the full scale and the resolution of the digital rule is 0.01 mm. The dynamometer is actuated manually with a handwheel connected to a lead screw, while its displacement is measured by the digital rule. A rigid cylindrical indentor (3.8 mm in diameter) with a flat end, connected to the dynamometer, was used. The indentor size was selected among the different heads of the apparatus as a compromise: smaller diameters would increase the pressure limiting the maximum force applicable for avoiding subject's pain; bigger diameters would cause overlapping of different point zones, as in points 10, 14 and 18, for example.

Six increasing levels of indentation were measured at each hand point and in the same session for each subject. Two additional repetitions of the experiment were performed in different days. The same operator performed all the experiments. During the measurements the subject's hand was fixed, outstretched and relaxed. Subjects were instructed to prevent muscular activation during the experiments. Depending on the tested point, the apparatus was used in vertical or horizontal position and the subject was instructed to adopt specific and repeatable postures of the body, arm and hand to reach a comfortable position (Figure 2). The measurement point was aligned with the indentor keeping the tangent plane to the hand surface at this point perpendicular to the indentation direction. Specially designed rigid blocks were used to ensure proper orientation of the hand with respect to the indentor and to ensure the subject's hand and arm were kept in a comfortable posture. The subject was instructed to keep his or her hand still during measurements on a same point. The indentor was displaced until the subject first felt contact with it. Then, the digital displacement rule was reset to zero. To obtain the measurement at the first indentation level, the dynamometer was displaced manually using the handwheel to increase indentation into the surface of the hand until a force magnitude of 1 N was achieved. The corresponding displacement of the digital rule was registered. This procedure was repeated with increments of 1 N until a force of 6 N was reached. Care was taken to ensure that the indentation rate was kept slow enough to minimise the effect of the viscoelastic response of the soft tissues. Approximately 10 seconds were necessary to complete the measures on one point. The lead screw was irreversible, thus allowing to maintain the displacement reading once the force was first reached in the dynamometer; a slight force relaxation was observed during the time used to read the displacement in the rule display. In a few repetitions of the measurement of some points and for some subjects (0.4%, 10 individual measurements in all), displacement with a force of 6 N was not measured because the pain was reported as excessive. However, at least one measurement was obtained in all points and subjects.

The levels of indentation considered defined 6 force intervals. The stiffness (N/mm) for each force interval was calculated as

$$s_{i,i+1} = \frac{F_{i+1} - F_i}{X_{i+1} - X_i} = \frac{1N}{X_{i+1} - X_i}$$

where X_i is the absolute displacement when applying force F_i, and F_0= 0 N, F_1= 1 N, …, F_6= 6 N. Therefore a total of 6 values of stiffness were obtained for each point, subject and repetition (each one in different days).

First, the repeatability of the measures was analysed. For each stiffness interval, the repeatability error was estimated as the root mean squared error (RMSE) from an ANOVA on stiffness with the factors *subject* and *point* and their interaction. The variability in this ANOVA is only associated with the three repetitions of the measurements.

Second, the three repetitions at each point and subject were compared to detect outliers. The MAD (Median Absolute Deviation) method was used for this purpose. This method is considered to be one of the more robust methods that can be applied to small data sets (Huber, 2004; Rousseeuw and Croux, 1993). When the absolute difference between one of the repetitions and the median of all three repetitions was bigger than five times the MAD of the three repetitions, the value was considered an outlier and substituted by the mean of the other two repetitions. The values that were missing because of the above-mentioned reported pain at the 6 N force level, were also substituted by the mean of the other repetitions.

Subsequently, an analysis of the similarity of stiffness at different points was performed. Five initially expected groupings were made: tips (points 1-5), joint regions (6-10 and 15-18), segmental regions (11-14 and 19-23), palm (24-30 and 39) and lateral regions (31-38). These groups were selected according to the role of the points in different grasp types and the anatomical similarities. A similar behaviour in the stiffness change with force was expected in each group. To check whether the mean value of the stiffness at the different points of the same initial groups was also similar, five one-way ANOVAs (one per group) were performed. Stiffness was included as the dependent variable and the point as the independent factor. For each analysis, the data of all subjects, repetitions and intervals were used. Post-hoc Tukey's test with a level of significance $p=0.05$ was used to detect homogeneous points inside each initial grouping. When a set of points in one of the initial groups had no significant differences between them but did show significant differences with the remaining points in the group, these points were considered a different region, and the original grouping was subdivided. The regions of points obtained in this way are described and results are presented grouped by these regions.

Finally, the influence of personal factors such as gender and BMI in the observed variability of stiffness was checked using a general linear model (dependent variable: *stiffness*; factors: *gender, region, interval*; covariable: *BMI*) and partial correlations.

3. Results

A non-linear relationship was observed between force and displacement in the different points of the hand, this relationship being different from one point to another. Figure 3 shows typical results for some points in one of the subjects, with both measured data and curve fitting to power laws (mean displacements by force and point in Appendix). Although stiffness was always observed to increase with the level of displacement or force, a different force-displacement response was observed from point to point, depending on its location on the hand. At some points, such as the fingertips (see point 2 in Figure 3), stiffness changes importantly from small displacements to larger ones, whereas at other points (see point 34 in Figure 3) stiffness is far more constant regardless of the displacement level.

Table 2 shows the RMSE from the ANOVAs used to estimate the repeatability errors associated to the three repetitions of the measurements, before and after the correction of outliers, together with the mean stiffness per force interval. The absolute values of the repeatability errors increased with the force interval. The percentage of outliers removed from the initial data was 10.5% and similar across all the points (ranging from 7.2% to 12.5%) or the subjects (ranging from 8.4% to 12.8%).

Thirteen different regions with similar mean stiffness were identified from the Tukey's test. The groups of points obtained are summarised in Table 3.

Detailed numeric data with the mean and standard deviation of stiffness for each force interval at each point and region are included in the Appendix. Table 4 presents the mean and standard deviation of the results by region. Figure 4 shows a graph for each region, in which the mean value of stiffness for each point of the region is plotted against the force interval. The 95% confidence intervals (CI) for the mean are also shown. It can be observed that the groups were quite homogeneous, i.e. the curves observed in each region were quite similar, whereas the confidence intervals were quite different depending on points and interval. In some regions the increase in stiffness with displacement was quite linear (e.g. distal phalanges), whereas in other regions stiffness tended to increase less for larger displacements (e.g. palm). Moreover, the biggest difference in stiffness from a small to a larger displacement was observed in the distal phalanges.

At most points, the CI for the mean increased by a significant amount from the second interval of force onwards. The smallest CI were observed for the medial and proximal palm points, while the highest CI were obtained for the points on the lateral side of joints of the thumb and the index finger.

The results of the general linear model for *stiffness* performed with the factors *gender*, *region* and *interval*, and *BMI* as a covariable are shown in Table 5. *Interval* and *region*, and their interaction, as expected, were significant factors. *BMI* was a significant variable and had a negative coefficient in the model, indicating a decrease in stiffness for greater BMI. However, the only significant factor including gender was the interaction *gender*region*. In this case, the estimated marginal means of the interaction showed that only in two regions the differences in gender were statistically significant: in the MP and DP_F regions the stiffness was higher for women than for men. To check whether the effect of BMI differs depending on the region, partial correlation coefficients of *BMI* with *stiffness*, controlling for *interval*, were calculated for each region. In all the regions, the correlation coefficients were negative, but only in some of them were statistically significant ($p<0.05$, $*p<0.01$): DP_F*, MP, Joint_PIP, Lat_Joint, Lat_MP_I and D_Palm*.

4. Discussion

In this work, the force-displacement response in the different hand areas that may come into contact with objects when grasping has been measured. A non-linear relationship was observed between force and displacement at the different points of the hand, which agrees with previous works (Gulati and Srinivasan, 1995; Serina et al., 1997; Srinivasan and Dandekar, 1996). Data reported in the literature that can be used to compare with our results are scarce, because no previous studies have tried to characterise the stiffness of the different parts of the hand; only the stiffness of the fingertip pulp (Gulati and Srinivasan, 1995) and that of the thenar eminence (Sandford et al., 2013) have been analysed. For the index fingertip, our displacement results for 1 N force (3.71 mm) are similar to those obtained by Gulati and Srinivasam (3 mm), being the difference justified by the smaller indentor diameter used in the present work (3.8 mm vs. 6.35 mm). Only the values for an applied force of 1 N can be compared, as stiffness was measured for forces lower than 1 N in that work, and for forces from 1 N to 6 N in the present work. The maximum force level of 6 N is in the range of the contact force reported for pinch grip with objects of 500 gr to 600 gr weight (Edin et al., 1992, Bourbonnais et al., 2008). On the other hand, the accuracy of the measuring equipment used in the present work has not allowed measurement of the force-displacement response for forces lower than 1 N. The data reported by Gulati and Srinivasan for the index fingertip are complementary to the data obtained in this work, for the cases where the grasp may require very small contact forces. However, if needed, the data from the present work can be extrapolated by taking into account the shape of the curves obtained by those authors for the lowest force interval. For the thenar eminence Sandford et al. (2013) obtained a stiffness value around 0.5 N/mm with a force level between 1.2-1.5 N, which is comparable to the value obtained in our work for points 24 (0.490 N/mm) and 29 (0.589 N/mm) for the interval between 1 N and 2 N.

Our results also indicate that stiffness increases in the fingertips almost linearly with the force applied, which is in accordance with the results reported by Jindrich et al. (2003). The stiffness value obtained for the fingertips is also similar to that obtained in the cited work. However, our results show that this linear increase in stiffness with the force applied does not happen in other regions of the hand, especially when moving proximally towards the palm, where stiffness tends to remain more constant regardless of the force applied.

It has been shown how the stiffness data obtained for the 39 points on the hand can be reduced significantly to 13 different regions with similar stiffness behaviour. In general, analogous points on the index and thumb have been included in the same group, with the exception of the distal phalange of the thumb, maybe because of the particular role played by the thumb in grasping. It is hypothesised that the differences in the stiffness behaviour from one region to another allow these regions to carry out different roles during grasping. Lower stiffness has been found for the palm compared to other regions, which highlights the cushioning role played by the palm during power grasps. The distal phalanges accounted for the biggest difference in stiffness from a small to a larger displacement, thus allowing them to participate in both precision and power grasps.

Some accuracy problems arose during the data processing because of the method used to obtain the stiffness. A small error in the registration of one displacement leads to greater stiffness in one interval and smaller stiffness in the consecutive interval. As a consequence, some very high stiffness values (35 N/mm) were obtained in some cases. This was dealt with by means of the correction of the outliers, resulting in smaller repeatability errors. These errors, however, have been found to increase with the force applied, which explains why the CI for most of the regions increased with the force interval. The differences in the CI between the palmar and lateral sides of the distal phalanges, for example, can be attributed to small differences in the placement of the indentor on an area where the underlying bone has a high degree of curvature, or even to eventual small changes in hand posture, resulting in displacements of the indentor either in the volar or dorsal directions, and changing the force-displacement response. This same effect could also be behind the decline in stiffness with increasing force observed in some points, as 26 or 28. Another concern about the accuracy of the stiffness values obtained is that the hand was supported on a block and consequently the actual stiffness may be higher than measured because the soft-tissue contacting the block in the dorsal side will contribute to the measurements. However, this effect is probably negligible, because the contacting surface in the back side is much greater than that of the indentor, thus having small effect on the measured displacement.

One limitation of this work is that the data were obtained using only one indentor with a diameter of 3.8 mm. The existence of dependence between the reported stiffness data and the diameter of the indentor is assumed, and this must be considered when interpreting the results. This effect could be analysed in future works. Another limitation is that the stiffnesses reported here were obtained with the hand stretched and relaxed and they may vary for other postures. Two effects have to be considered for flexed postures: changes in skin geometry and changes in muscles conformation. Rogers et al. (2008) reported changes in the skin geometry of the hand in flexed postures. These changes in geometry could affect especially in the areas close to the finger joints, where a decrease in the stiffness values can be expected. Additionally, in skin areas over intrinsic muscles, as the thenar region, the stiffness may be affected depending on the muscle conformation and on the activation level.

The data obtained in this work can be used in the context of grasping simulation to model the relationship between the local contact forces at the different points of the hand and the local deformation, using soft contact models as those proposed by Ciocarlie et al. (2005, 2007). Friction forces in the contact can be modelled indirectly from the normal forces using appropriate friction models (Ciocarlie et al., 2005). In this context, it is important to highlight the dependence of stiffness on BMI observed in the present work. Furthermore, the above-mentioned changes of stiffness with posture and muscle activation could be a source of error. More work is needed to clarify the changes in stiffness at each point depending on posture and muscles activation.

The reported data are also relevant for selecting the covering materials for use in hand prostheses, in order to achieve a compliant design similar to the real hand that helps avoid stability problems (Weir, 2004). In this case, it might be interesting to consider the mean stiffness values per region so as to be able to reduce the set of different materials required. The data can also be of interest in Ergonomics, where they could be used to provide additional cushioning in hand contact areas which have higher stiffness. By so doing, it would be possible to avoid excessive contact pressures and reduce the level of transmitted vibrations.

Furthermore, the stiffness data obtained can be used as a reference for the normal stiffness of soft tissue in the different parts of the hand of healthy individuals, with a possible clinical application as a means to distinguish between normal and pathological tissue function. However, more research is required to explore the feasibility of using the stiffness to distinguish between normal and pathological tissue function, including the analysis of pressure limits to avoid additional damage to the pathological tissues.

Disclosure of potential conflict of interest

The authors declare that no conflict of interest exists.

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References

Bourbonnais, D., Frak, V., Pilon, J. -., Goyette, M., 2008. An instrumented cylinder measuring pinch force and orientation. Journal of NeuroEngineering and Rehabilitation 5.

Boyer, G., Laquièze, L., Le Bot, A., Laquièze, S., Zahouani, H., 2009. Dynamic indentation on human skin in vivo: ageing effects. Skin Research and Technology 15, 55-67.

Ciocarlie, M., Lackner, C., Allen, P., 2007. Soft Finger Model with Adaptive Contact Geometry for Grasping and Manipulation Tasks.. In .

Ciocarlie, M., Miller, A., Allen, P., 2005. Grasp analysis using deformable fingers. In IEEE IRS/RSJ International Conference on Intelligent Robots and Systems, IROS 2005, Edmonton, AB.

Cutkosky, M. R., Howe, R. D., 1990. Human Grasp Choice and Robotic Grasp Analysis. Springer-Verlag, New-York, pp. 5-31.

Dandekar, K., Raju, B. I., Srinivasan, M. A., 2003. 3-D finite-element models of human and monkey fingertips to investigate the mechanics of tactile sense. Journal of Biomechanical Engineering 125, 682-691.

Dong, R. G., Wu, J. Z., Welcome, D. E., 2005. Recent Advances in Biodynamics of Human Hand-Arm System. Industrial Health 43, 449-471.

Edin, B. B., Westling, G., Johansson, R. S., 1992. Independent control of human finger-tip forces at individual digits during precision lifting. The Journal of Physiology 450, 547-564.

Gulati, R. J., Srinivasan, M. A., 1995. Human fingerpad under indentation I: static and dynamic force response. In Bioengineering Conference Division, ASME, Vol. 29.

Huber, P. J., 2004. Robust Statistics. Wiley, .

Jindrich, D. L., Zhou, Y., Becker, T., Dennerlein, J. T., 2003. Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping. Journal of Biomechanics 36, 497-503.

Kargov, A., Pylatiuk, C., Martin, J., Schulz, S., Doderlein, L., 2004. A comparison of the grip force distribution in natural hands and in prosthetic hands. Disability and Rehabilitation 26, 705-711.

Pataky, T. C., Slota, G. P., Latash, M. L., Zatsiorsky, V. M., 2012. Radial force distribution changes associated with tangential force production in cylindrical grasping, and the importance of anatomical registration. Journal of Biomechanics 45, 218-224.

Rogers, M. S., Barr, A. B., Kasemsontitum, B., Rempel, D. M., 2008. A three-dimensional anthropometric solid model of the hand based on landmark measurements. Ergonomics 51, 511-526.

Rousseeuw, P. J., Croux, C., 1993. Alternatives to the Median Absolute Deviation. Journal of the American Statistical Association 88, 1273-1283.

Sancho-Bru, J. L., Pérez-González, A., Mora, M. C., León, B. E., Vergara, M., Iserte, J. L., Rodríguez-Cervantes, P. J., Morales, A., 2011. Towards a Realistic and Self-Contained Biomechanical Model of the Hand, InTech.

Sandford, E., Chen, Y., Hunter, I., Hillebrand, G., Jones, L., 2013. Capturing skin properties from dynamic mechanical analyses. Skin Research and Technology 19, e339-e348.

Schlereth, T., Magerl, W., Treede, R., 2001. Spatial discrimination thresholds for pain and touch in human hairy skin. Pain 92, 187-194.

Serina, E. R., Mote, C. D.,Jr, Rempel, D., 1997. Force response of the fingertip pulp to repeated compression--effects of loading rate, loading angle and anthropometry. Journal of Biomechanics 30, 1035-1040.

Serina, E. R., Mockensturm, E., Mote Jr., C. D., Rempel, D., 1998. A structural model of the forced compression of the fingertip pulp. Journal of Biomechanics 31, 639-646.

Shima, K., Tamura, Y., Tsuji, T., Kandori, A., Yokoe, M., Sakoda, S., 2009. Estimation of human finger tapping forces based on a fingerpad-stiffness model. In Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE.

Srinivasan, M. A., Dandekar, K., 1996. An investigation of the mechanics of tactile sense using two-dimensional models of the primate fingertip. Journal of Biomechanical Engineering 118, 48-55.

Weir, R. F., 2004. Design of artificial arms and hands for prosthetic applications. McGraw-Hill, pp. 32.1.

Table 1. Descriptive statistics of age and anthropometric parameters of the sample, BMI: body mass index, HL: hand length (from the proximal palmar crease to the tip of the third digit) , HB: hand breath (at the metacarpal heads), SD: standard deviation.

	Mean	SD	Minimum	Maximum
Age	27.2	8.1	22	57
Weight (kg)	67.7	11.1	50	90
Stature (cm)	170	7	156	183
BMI (kg/m^2)	23.28	3.13	18.82	31.14
HL (cm)	18.08	1.03	16.7	21.0
HB (cm)	8.27	0.62	7.4	9.5

Table 2. Repeatability errors associated to the three repetitions by force interval.

	RMSE previous to correction of outliers (N/mm)	RMSE after correction of outliers (N/mm)	Mean value of stiffness (N/mm)
s01	0.15	0.12	0.46
s12	1.09	0.70	1.96
s23	1.33	0.96	2.89
s34	1.55	1.02	3.30
s45	1.55	1.14	3.94
s56	1.61	1.29	4.10

Table 3. Classification of points in regions with similar mean stiffness.

Region	Nick	Points
Distal phalange of thumb	DP_T	1
Distal phalanges of fingers	DP_F	2,3,4,5
Distal interphalangeal joints	Joint_DIP	7,8,9,10
Proximal interphalangeal joints	Joint_PIP	6,15,16,17,18
Intermediate phalanges	MP	11,12,13,14
Proximal phalanges	PP	19,20,21,22,23
Medial and proximal palm	M&P_Palm	24,29,30,39
Distal palm middle finger	D_Palm_M	26
Rest of distal palm	D_Palm	25,27,28
Lateral side of distal phalange of thumb	Lat_DP_T	31
Lateral side of intermediate phalange of index	Lat_MP_I	36
Lateral side of joints of thumb and index	Lat_Joint	33,34,37
Rest of lateral side of proximal and distal phalanges	Lat_P&D	32,35,38

Table 4. Mean (SD) of the stiffness (N/mm) by region and force interval (20 subjects)

	Force interval					
	s01	s12	s23	s34	s45	s56
DP_T	0.23(0.04)	1.37(0.44)	2.45(0.73)	3.25(1.00)	4.20(1.37)	4.67(1.81)
DP_F	0.27(0.04)	1.86(0.63)	3.61(1.27)	4.72(1.41)	6.12(1.61)	6.88(1.94)
Joint_DIP	0.50(0.13)	2.38(1.12)	3.96(1.55)	4.83(1.33)	6.01(1.79)	6.64(2.14)
Joint_PIP	0.80(0.30)	2.76(1.13)	3.56(1.45)	3.66(1.44)	4.00(1.69)	4.16(1.74)
MP	0.35(0.09)	1.48(0.57)	2.60(1.06)	3.45(1.15)	4.41(1.53)	4.64(1.63)
PP	0.28(0.07)	1.18(0.43)	1.95(0.90)	2.33(0.95)	2.88(1.30)	2.95(1.31)
M&P_Palm	0.24(0.09)	0.55(0.18)	0.74(0.26)	0.83(0.30)	1.03(0.41)	1.10(0.55)
D_Palm_M	0.36(0.12)	1.71(0.86)	2.38(0.94)	2.16(1.20)	2.47(1.45)	1.88(0.96)
D_Palm	0.30(0.12)	1.25(0.60)	1.78(0.91)	1.95(1.16)	2.03(0.98)	1.87(0.90)
Lat_DP_T	0.44(0.12)	1.45(0.59)	1.98(0.75)	2.17(0.61)	2.75(0.79)	2.83(0.97)
Lat_MP_I	0.93(0.42)	3.10(1.54)	3.73(1.31)	4.02(1.19)	4.98(1.67)	4.62(1.70)
Lat_Joint	0.92(0.28)	4.03(1.57)	5.52(2.15)	5.40(2.16)	6.12(2.28)	5.76(2.07)
Lat_P&D	0.50(0.18)	2.67(1.47)	3.06(1.24)	3.19(1.31)	3.43(1.39)	3.51(1.74)

Table 5. Results of the general linear model.

Tests of Between-Subjects Effects					
Dependent Variable: Stiffness (N/mm)					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	46500.461[a]	156	298.080	202.349	0.000
Intercept	2258.062	1	2258.062	1532.863	0.000
BMI	62.028	1	62.028	42.107	0.000
Region	17843.907	12	1486.992	1009.430	0.000
Interval	13880.160	5	2776.032	1884.482	0.000
Gender	0.564	1	0.564	0.383	0.536
Region * Interval	6299.455	60	104.991	71.272	0.000
Region * Gender	94.557	12	7.880	5.349	0.000
Interval * Gender	2.485	5	0.497	0.337	0.891
Region * Interval * Gender	103.476	60	1.725	1.171	0.173
Error	20449.585	13882	1.473		
Total	175071.309	14039			
Corrected Total	66950.046	14038			

a. R Squared = 0.695 (Adjusted R Squared = 0.691)

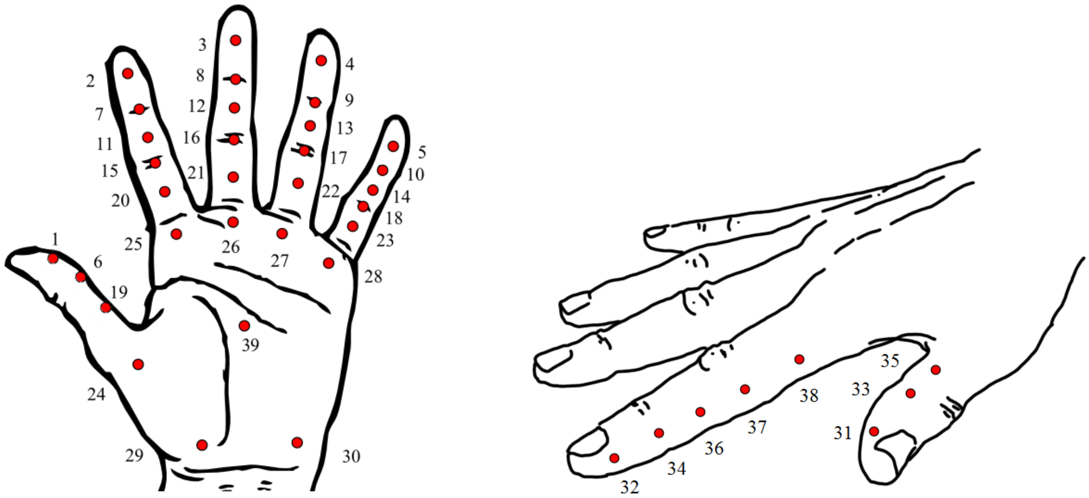

Figure 1. Location of the points for measurement on the hand.

Figure 2. Examples of experimental setup for different test points.

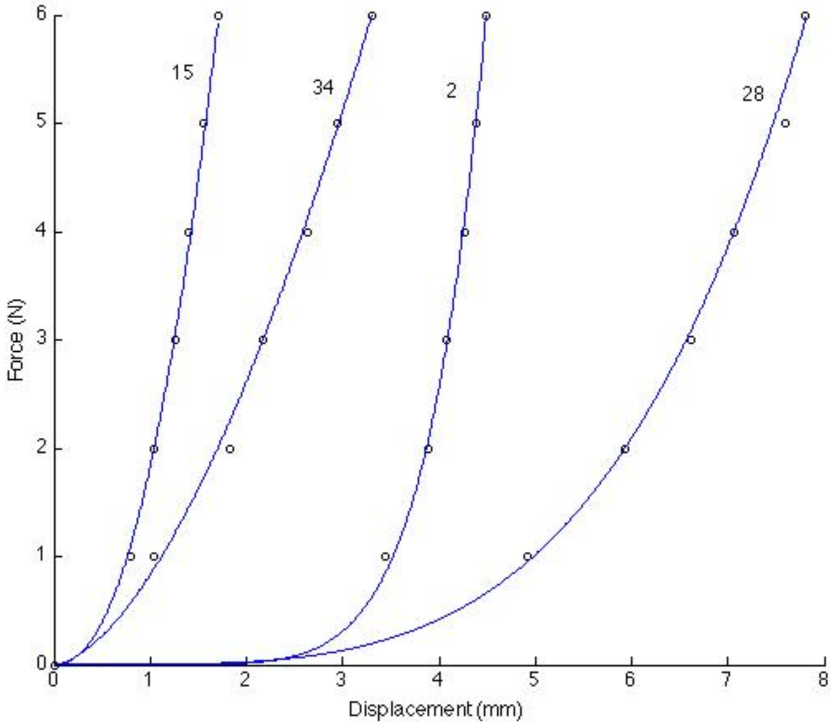

Figure 3. Typical curves of force F versus displacement X (subject 1, repetition 1, points 2, 15, 28, 34).

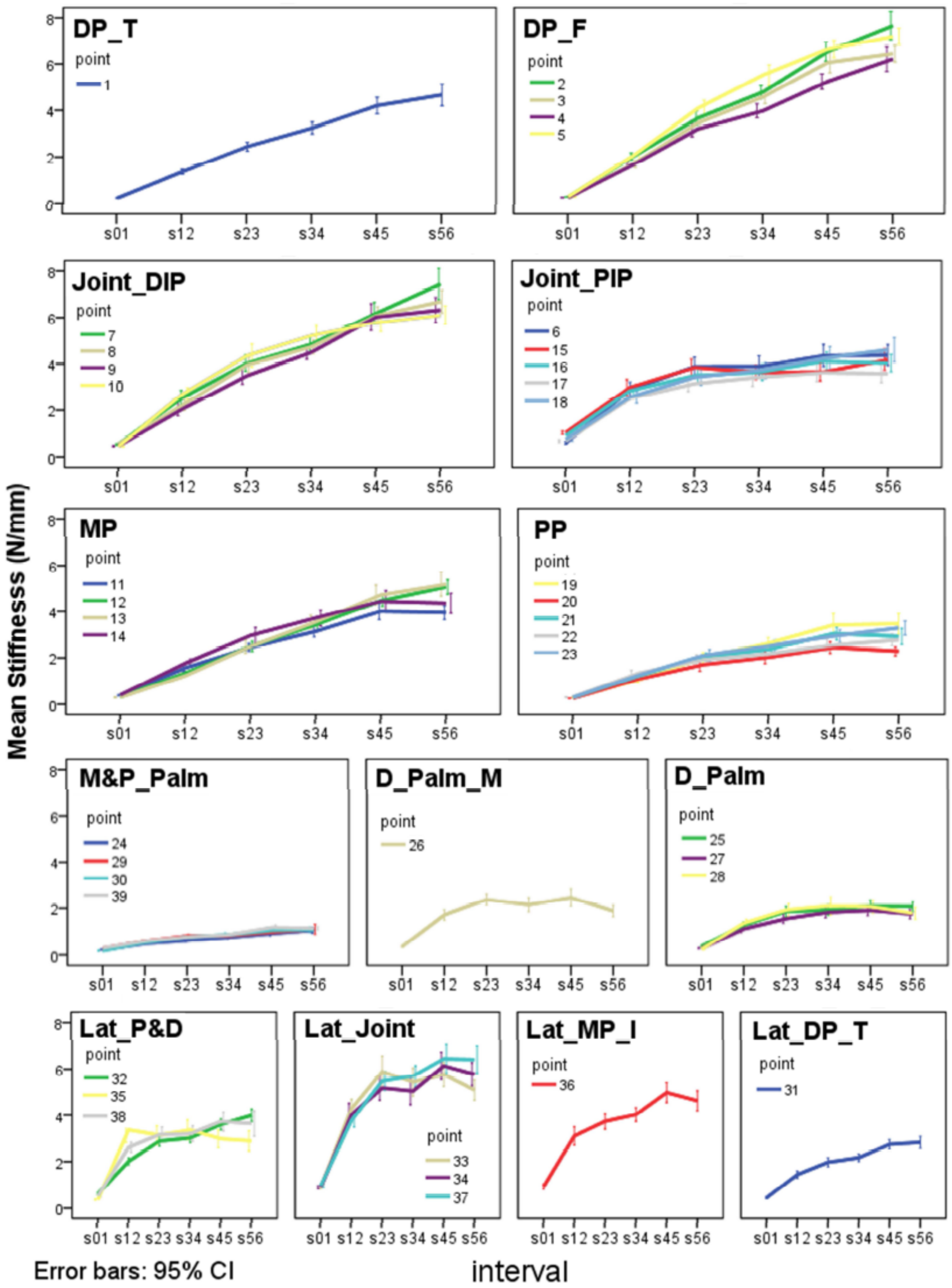

Figure 4. Mean value of stiffness per point and regions with 95% CI for the mean.

Appendix

Mean (SD) of displacement (mm) by force for each point (20 subjects)

Point	D (1N)	D (2N)	D (3N)	D (4N)	D (5N)	D (6N)
1	4.27(0.77)	5.12(0.78)	5.57(0.78)	5.91(0.84)	6.17(0.87)	6.41(0.88)
2	3.71(0.62)	4.25(0.61)	4.54(0.63)	4.76(0.64)	4.93(0.65)	5.09(0.68)
3	4.04(0.43)	4.67(0.48)	5.00(0.52)	5.23(0.54)	5.41(0.56)	5.57(0.57)
4	4.00(0.62)	4.69(0.56)	5.04(0.59)	5.32(0.62)	5.52(0.65)	5.70(0.68)
5	3.47(0.60)	4.01(0.67)	4.28(0.71)	4.49(0.74)	4.66(0.76)	4.80(0.78)
6	1.80(0.65)	2.25(0.75)	2.58(0.82)	2.89(0.88)	3.20(0.94)	3.46(0.99)
7	1.94(0.42)	2.38(0.44)	2.66(0.48)	2.88(0.51)	3.06(0.52)	3.21(0.54)
8	1.91(0.46)	2.42(0.54)	2.70(0.54)	2.93(0.54)	3.11(0.54)	3.28(0.58)
9	2.32(0.68)	3.00(0.81)	3.32(0.82)	3.55(0.83)	3.75(0.86)	3.91(0.87)
10	2.35(0.54)	2.79(0.55)	3.04(0.56)	3.25(0.56)	3.43(0.57)	3.60(0.57)
11	2.73(0.61)	3.44(0.70)	3.88(0.75)	4.22(0.78)	4.50(0.80)	4.78(0.81)
12	3.24(0.69)	4.01(0.68)	4.44(0.68)	4.75(0.68)	4.99(0.67)	5.21(0.69)
13	3.55(0.73)	4.46(0.90)	4.95(0.91)	5.29(0.93)	5.53(0.97)	5.75(0.99)
14	2.66(0.68)	3.30(0.76)	3.70(0.82)	4.01(0.87)	4.28(0.90)	4.54(0.94)
15	1.04(0.32)	1.43(0.39)	1.74(0.43)	2.03(0.50)	2.34(0.54)	2.62(0.59)
16	1.20(0.44)	1.61(0.50)	1.95(0.58)	2.28(0.64)	2.57(0.71)	2.87(0.73)
17	1.63(0.55)	2.07(0.60)	2.47(0.67)	2.83(0.74)	3.16(0.80)	3.48(0.83)
18	1.54(0.59)	1.98(0.70)	2.35(0.77)	2.66(0.81)	2.94(0.87)	3.13(0.97)
19	3.64(0.89)	4.77(1.06)	5.37(1.16)	5.83(1.20)	6.20(1.21)	6.57(1.33)
20	4.03(0.77)	5.06(0.86)	5.75(0.96)	6.32(1.07)	6.81(1.15)	7.31(1.20)
21	3.71(0.68)	4.59(0.75)	5.13(0.84)	5.60(0.89)	5.98(0.95)	6.37(0.99)
22	3.51(0.86)	4.36(1.00)	4.98(1.13)	5.50(1.22)	5.97(1.25)	6.40(1.30)
23	3.58(1.04)	4.46(1.18)	5.03(1.24)	5.50(1.26)	5.89(1.27)	6.25(1.31)
24	4.98(1.54)	7.25(2.00)	9.06(2.28)	10.54(2.37)	11.74(2.46)	11.96(4.11)
25	2.99(0.94)	3.87(1.12)	4.52(1.20)	5.16(1.30)	5.77(1.50)	6.38(1.70)
26	3.03(0.93)	3.72(1.11)	4.27(1.34)	4.86(1.55)	5.40(1.68)	5.93(2.00)
27	3.87(1.07)	5.02(1.37)	5.83(1.61)	6.55(1.86)	7.21(2.12)	7.76(2.60)
28	4.29(1.06)	5.22(1.33)	5.94(1.54)	6.70(1.80)	7.36(2.07)	7.99(2.54)
29	3.97(1.19)	5.76(1.54)	7.19(1.92)	8.62(2.34)	9.78(2.63)	10.98(2.91)
30	5.78(1.36)	7.81(1.69)	9.27(1.84)	10.7(2.16)	11.79(2.39)	12.75(3.13)
31	2.42(0.61)	3.15(0.66)	3.70(0.74)	4.20(0.81)	4.62(0.89)	5.09(1.09)
32	1.67(0.44)	2.21(0.51)	2.59(0.58)	2.96(0.65)	3.27(0.72)	3.55(0.80)
33	1.18(0.35)	1.44(0.37)	1.65(0.41)	1.87(0.47)	2.06(0.51)	2.28(0.54)
34	1.15(0.31)	1.44(0.33)	1.65(0.35)	1.88(0.38)	2.07(0.40)	2.26(0.45)
35	2.88(0.70)	3.26(0.74)	3.66(0.89)	4.10(1.11)	4.51(1.27)	4.95(1.46)
36	1.24(0.43)	1.61(0.47)	1.90(0.51)	2.16(0.55)	2.41(0.62)	2.66(0.70)
37	1.12(0.48)	1.41(0.59)	1.62(0.65)	1.82(0.75)	2.00(0.82)	2.22(0.93)
38	2.12(0.68)	2.52(0.70)	2.88(0.77)	3.27(0.92)	3.62(1.05)	4.06(1.35)
39	3.69(0.91)	5.47(1.18)	6.88(1.30)	8.12(1.49)	9.04(1.56)	9.94(1.62)

Mean (SD) of stiffness (N/mm) by points and interval (20 subjects)

Point	S01	S12	S23	S34	S45	S56
1	0.232 (0.037)	1.371 (0.443)	2.453 (0.735)	3.249 (0.999)	4.205 (1.368)	4.666 (1.815)
2	0.275 (0.042)	2.024 (0.582)	3.675 (1.179)	4.790 (1.114)	6.539 (1.599)	7.660 (2.390)
3	0.250 (0.026)	1.703 (0.570)	3.467 (1.145)	4.580 (1.146)	6.060 (1.738)	6.439 (1.376)
4	0.252 (0.033)	1.671 (0.539)	3.209 (1.295)	3.981 (1.150)	5.244 (1.257)	6.211 (2.085)
5	0.288 (0.041)	2.057 (0.709)	4.095 (1.313)	5.519 (1.715)	6.644 (1.467)	7.190 (1.397)
6	0.602 (0.209)	2.889 (1.294)	3.879 (1.629)	3.888 (1.801)	4.359 (1.847)	4.379 (1.728)
7	0.537 (0.130)	2.548 (1.230)	4.032 (1.360)	4.850 (1.235)	6.181 (1.837)	7.439 (2.627)
8	0.560 (0.146)	2.225 (0.909)	3.959 (1.248)	4.739 (1.164)	6.073 (1.555)	6.684 (1.894)
9	0.465 (0.131)	2.058 (1.161)	3.499 (1.442)	4.507 (1.160)	6.018 (2.235)	6.320 (2.122)
10	0.445 (0.095)	2.704 (1.055)	4.359 (1.954)	5.222 (1.634)	5.776 (1.471)	6.096 (1.595)
11	0.380 (0.089)	1.568 (0.640)	2.453 (0.652)	3.140 (0.953)	4.007 (1.410)	3.952 (1.163)
12	0.320 (0.070)	1.342 (0.330)	2.496 (0.867)	3.422 (1.065)	4.468 (0.963)	5.070 (1.223)
13	0.292 (0.059)	1.236 (0.407)	2.490 (1.144)	3.538 (1.160)	4.720 (1.703)	5.177 (1.999)
14	0.395 (0.104)	1.770 (0.691)	2.962 (1.358)	3.716 (1.349)	4.441 (1.840)	4.363 (1.687)
15	1.044 (0.287)	2.989 (1.341)	3.845 (1.423)	3.638 (1.188)	3.653 (1.482)	4.186 (1.781)
16	0.919 (0.267)	2.846 (0.951)	3.499 (1.406)	3.638 (1.347)	4.115 (1.559)	4.038 (1.466)
17	0.679 (0.229)	2.509 (0.944)	3.154 (1.322)	3.430 (1.505)	3.626 (1.496)	3.581 (1.487)
18	0.747 (0.289)	2.562 (1.035)	3.429 (1.377)	3.721 (1.316)	4.249 (1.937)	4.607 (2.038)
19	0.284 (0.066)	1.055 (0.446)	1.998 (0.871)	2.623 (0.985)	3.411 (1.914)	3.463 (1.735)
20	0.251 (0.044)	1.080 (0.304)	1.711 (1.099)	2.022 (1.052)	2.439 (0.984)	2.282 (0.773)
21	0.277 (0.053)	1.209 (0.293)	2.046 (0.641)	2.352 (0.773)	3.048 (1.088)	2.923 (1.329)
22	0.300 (0.072)	1.331 (0.522)	1.915 (0.833)	2.166 (0.804)	2.548 (1.001)	2.778 (1.025)
23	0.295 (0.091)	1.245 (0.490)	2.101 (0.978)	2.512 (0.982)	2.937 (1.036)	3.283 (1.179)
24	0.219 (0.093)	0.490 (0.181)	0.626 (0.200)	0.755 (0.258)	0.918 (0.323)	1.067 (0.499)
25	0.369 (0.130)	1.282 (0.490)	1.860 (0.835)	1.922 (0.916)	2.105 (0.974)	2.074 (0.881)
26	0.360 (0.121)	1.715 (0.864)	2.381 (0.944)	2.157 (1.205)	2.470 (1.453)	1.881 (0.962)
27	0.281 (0.097)	1.118 (0.606)	1.553 (0.751)	1.823 (0.897)	1.906 (0.860)	1.753 (0.765)
28	0.249 (0.079)	1.360 (0.661)	1.920 (1.076)	2.103 (1.554)	2.071 (1.098)	1.785 (1.026)
29	0.268 (0.091)	0.589 (0.214)	0.805 (0.317)	0.828 (0.354)	0.978 (0.387)	1.106 (0.833)
30	0.177 (0.040)	0.534 (0.149)	0.769 (0.244)	0.866 (0.327)	1.056 (0.451)	1.088 (0.471)
31	0.442 (0.121)	1.446 (0.586)	1.976 (0.745)	2.170 (0.612)	2.746 (0.791)	2.829 (0.972)
32	0.619 (0.152)	2.015 (0.612)	2.883 (0.824)	3.015 (0.791)	3.596 (0.930)	3.992 (1.070)
33	0.900 (0.271)	4.283 (1.566)	5.887 (2.654)	5.441 (2.379)	5.765 (2.034)	5.093 (1.711)
34	0.901 (0.257)	4.031 (1.873)	5.174 (2.035)	5.044 (2.292)	6.144 (2.300)	5.774 (1.946)
35	0.360 (0.098)	3.365 (2.126)	3.135 (1.537)	3.361 (1.682)	2.980 (1.468)	2.887 (1.698)
36	0.930 (0.417)	3.104 (1.538)	3.729 (1.310)	4.025 (1.186)	4.978 (1.673)	4.624 (1.695)
37	0.963 (0.321)	3.776 (1.164)	5.485 (1.622)	5.703 (1.752)	6.447 (2.464)	6.413 (2.316)
38	0.522 (0.167)	2.618 (0.843)	3.163 (1.248)	3.197 (1.309)	3.721 (1.593)	3.636 (2.126)
39	0.292 (0.065)	0.591 (0.166)	0.767 (0.218)	0.868 (0.219)	1.173 (0.440)	1.146 (0.270)