Mechanical responses and physical factors of the fingertip pulp

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Abstract: The images of the mechanical responses were analysed when the fingertip was pressed against a plateau plate, and the influence of the contact angle on the loading pressure and the mechanical responses was investigated. As a result, as the contact angle was smaller, the change ratios due to the loading pressure were significantly larger in the contact length, the contact width and the distortion of lateral-view area. These parameters were thought to be useful in clinical medicine as indices for the degrees of mechanical responses of the fingertip. The length of the central axis and the maximum width of the fingertip were inappropriate as the parameters to represent the mechanical responses of the fingertip. The maximum width of the fingertip scarcely changed. This does not reflect the compressibility of the fingertip, and the fingertip as a whole extended along the central axis and in the vertical direction, and the change was not reflected in the maximum width.

Key words: Fingertip, mechanical response, hand, biomechanics.

INTRODUCTION

Human fingertips change their shape and increase the contact area while touching an object. In grasping objects, it is important for fingertips with a convex and round shape to change their shape according to the surface shape of the objects. However, since power vectors and pressure exerted by the fingertips on objects are not stable due to the mechanical responses of the fingertips, the analysis of physical movements incurs many problems (Sakai *et al.* 1996).

Investigation of the mechanical dynamics involved in human fingertip responsiveness is not only important in the elucidation of the properties that change fingertip shape but also expected to help further development of the human–machine interface. This knowledge can be applied to the development of user-friendly switches and control panels on the basis of the change in contact surface when human fingertips manipulate switches. Furthermore, this information is useful within a clinical context, since hardening of the fingertip pulp from scaring following injury may make it difficult to manipulate machines.

To date, few studies have reported the mechanical responses of human fingertips, and the results are conflicting. Srinivasan *et al.* (1992) performed experiments in which the fingertips mechanically interacted with a cylinder filled with water, and measured the volume of the fingertips during the interaction. They found that the changes in the shape of the fingertips were not due mechanical compression (Srinivasan *et al.* 1992). Serina *et al.* (1997, 1998) examined the changes in the frontal view of the fingertips when they were pressed, and found that the elasticity in the fingertips was primarily due to the presence of fat under mechanical loading pressures of 1 N or lower and the mechanical responses of the fingertips became smaller due to the hardness of the phalanx under pressures of more than 1 N (Serina *et al.* 1997; Serina *et al.* 1998).

With respect to mechanical responsiveness, the involvement of the elasticity of the fingertips remains controversial and a number of factors have yet to be elucidated. As such, the purpose of this study was to investigate the *in vivo* mechanical responses of the human fingertips via video image analysis.

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METHODS

Participants

Seventeen healthy adult men were enrolled into this study. Participants averaged 21.7 years of age (range = 21–23),

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Figure 1 Three CCD cameras were installed around the platform of an electric scale to record finger images with two cameras and the liquid crystal monitor of the electric scale.

had an average height of 172.6 cm (range = 164–185) and an average body weight of 65.9 kg (range = 54.4–103.6).

Measurements

Three CCD cameras, XR7157 (equipped with a 6× macro lens, 270,000 pixels) by Carton, were installed around the platform of an electric scale BW-3200D (0.1–3,200 g measurement range; standard deviation = 0.06 g) by Shimazu to record finger images, with two cameras displayed on the liquid crystal monitor of the electric scale (Fig. 1). The right index finger of the participant was pressed against the platform of the electric scale at an angle of 15°, 30°, 45° and 60°, and the frontal and lateral views of the fingertip were video recorded with the two CCD cameras as mentioned above. The contact angle of the index finger was formed by the midline of the finger and the surface of the platform, and the pressure was increased from 0 to 5 N in 30 s (Fig. 2(a)). Three kinds of video images recorded by the three CCD cameras were displayed on the TV monitors via the PQS-1500C by Tsukamoto Musen, a unit used to display the four images simultaneously, with the integrated images recorded at 30 Hz, and the image size for recording was set at 640 × 480 pixels. The image compression method of MPEG1 was performed with hard disk recording software Win DVR (Inter Vieo Inc., ver 1.0) installed on a personal computer (CPU = 1.3 GHz; RAM = 236 Mbytes). Frame-by-frame still pictures of the video images were recorded in the BMP format, and the frontal and lateral views at loading pressures of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 N were analysed with the image analysis software by Scion (Scion image, ver 4.02). The error of this video-based analysis system was within 1% of value.

Index of the mechanical responses of the fingertip

To analyse the still video images, the following indices were measured:

1. *Contact length* (x): The length by the lateral view of the contact surface between the fingertip and the platform was adopted as the contact length (Fig. 2(b)).
2. *Contact width* (y): The width of the contact surface by the frontal view between the fingertip and the platform was adopted as the contact width (Fig. 2(c)).
3. *Length of the central axis* (z): By the lateral view of the finger, a vertical line L was drawn from the depression of the bent distal interphalangeal joint to the midline of the fingertip, and the distance between the cross point to the midline (P) and the tip of the midline (Q) was adopted as the length of the central axis (Fig. 2(d)).
4. *Maximum width* (w): The width of the fingertip by the frontal view was measured as the maximum width (Fig. 2(e)).
5. *Lateral-view area* (S): The area between the fingertip and the line L by the lateral view of the fingertip was measured as the lateral-view area (Fig. 2(f)).
6. *Distortion of the lateral-view area* ($[S - S_0]/S_0$): The basal value of the lateral-view area in the absence of any loading pressure was designated as S_0, and $(S - S_0)/S_0$ was calculated.

All of these indices were calculated separately at each loading pressure (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 N) at each contact angle, and these differences were analysed with the Scheffe's multiple comparison procedure without equal variance.

RESULTS

The contact length (*x*)

The contact length (x) against the loading pressure F with the contact angle θ as a parameter dramatically increased at $F < 0.05$ N, an increased less dramatically at $0.5 \text{ N} < F < 3$ N, and was almost unchanged at $F > 3$ N, irrespective of F values (Fig. 3(a)). When the averages of x at each loading pressure were compared, there was no statistical difference between $F = 0.5$ N and $F = 1.0$ N, but there was a statistical difference between 15° and 30°, as well as between 65° and 75° of the contact angle at each loading pressure from $F = 1.5$ N to $F = 4.5$ N ($P < 0.01$), and as the contact angle decreased, the increase in the contact length due to the increase of the loading pressure was more remarkable.

Contact width (*y*)

As in the case with x, the contact width (y) against the loading pressure F with the contact angle θ as a parameter sharply increased at $F < 0.05$ N, and increased less dramatically at $0.5 \text{ N} < F < 3$ N, and was almost unchanged at $F > 3$ N, irrespective of F values (Fig. 3(b)). When the averages of y at each loading pressure were compared, there was no statistical difference at $F = 0.5$–2.0 N, but

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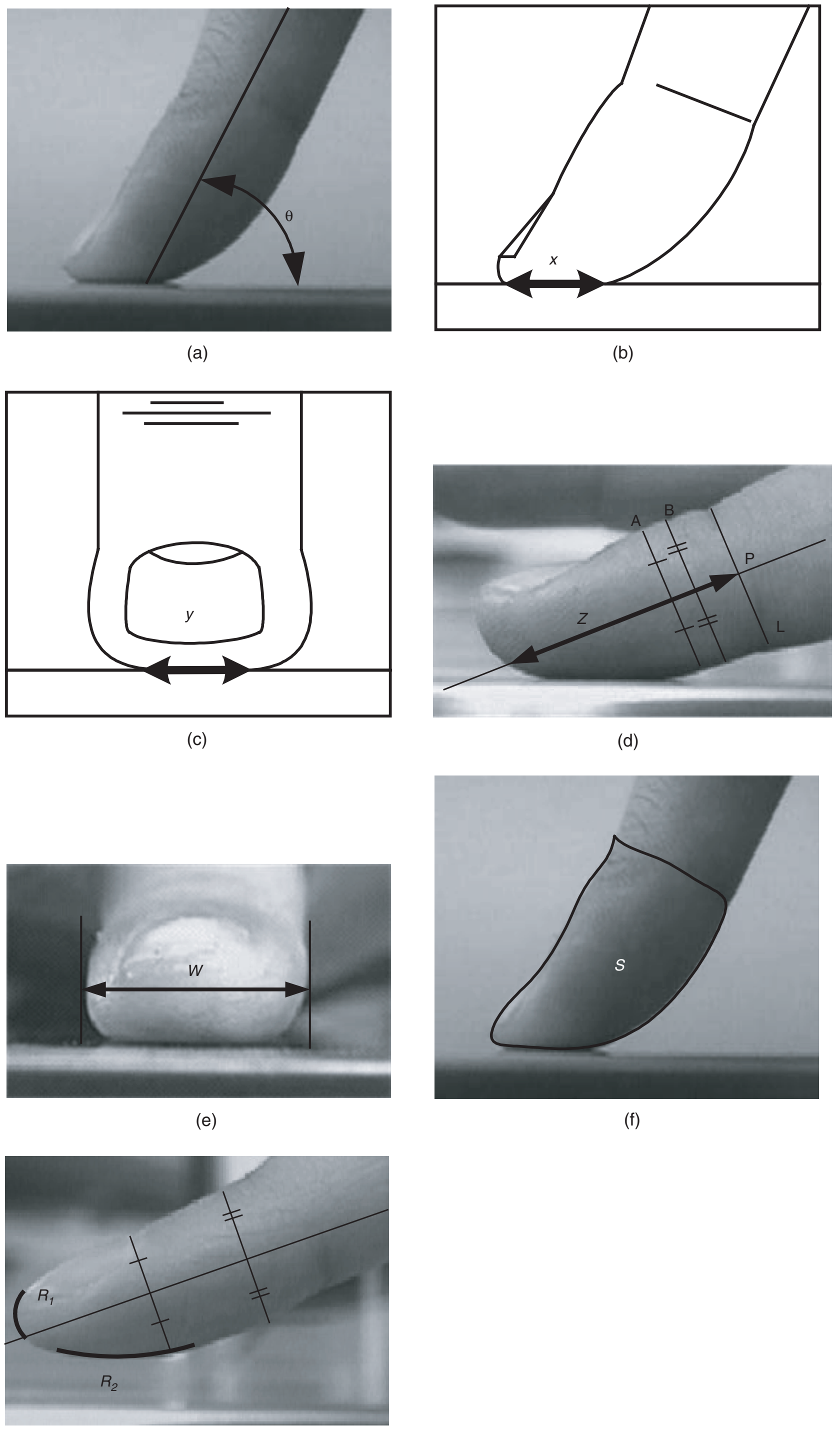

Figure 2 (a) The contact angle of the index finger was formed by the midline of the finger and the surface of the platform. (b) The contact length (x): The length by the lateral view of the contact surface between the fingertip and the platform was adopted as the contact length. (c) The contact width (y): The width of the contact surface by the frontal view between the fingertip and the platform was adopted as the contact width. (d) The length of the central axis (z): By the lateral view of the finger, a vertical line L was drawn from the depression of the bent distal interphalangeal joint to the midline of the fingertip, and the distance between the cross point to the midline (P) and the tip of the midline (Q) was adopted as the length of the central axis. (e) The maximum width (w): The width of the fingertip by the frontal view was measured as the maximum width. (f) The lateral-view area (S): The area between the fingertip and the line L by the lateral view of the fingertip was measured as the lateral-view area. (g) The radius of the curved surface from the cross point between the central axis of the fingertip and the surface of the finger tip to the tip of the nail was calculated as the curvature radius of the fingertip. Similarly, the curvature radius at the fingertip contacting the ceiling plate was measured and employed as the curvature radius of the contact area.

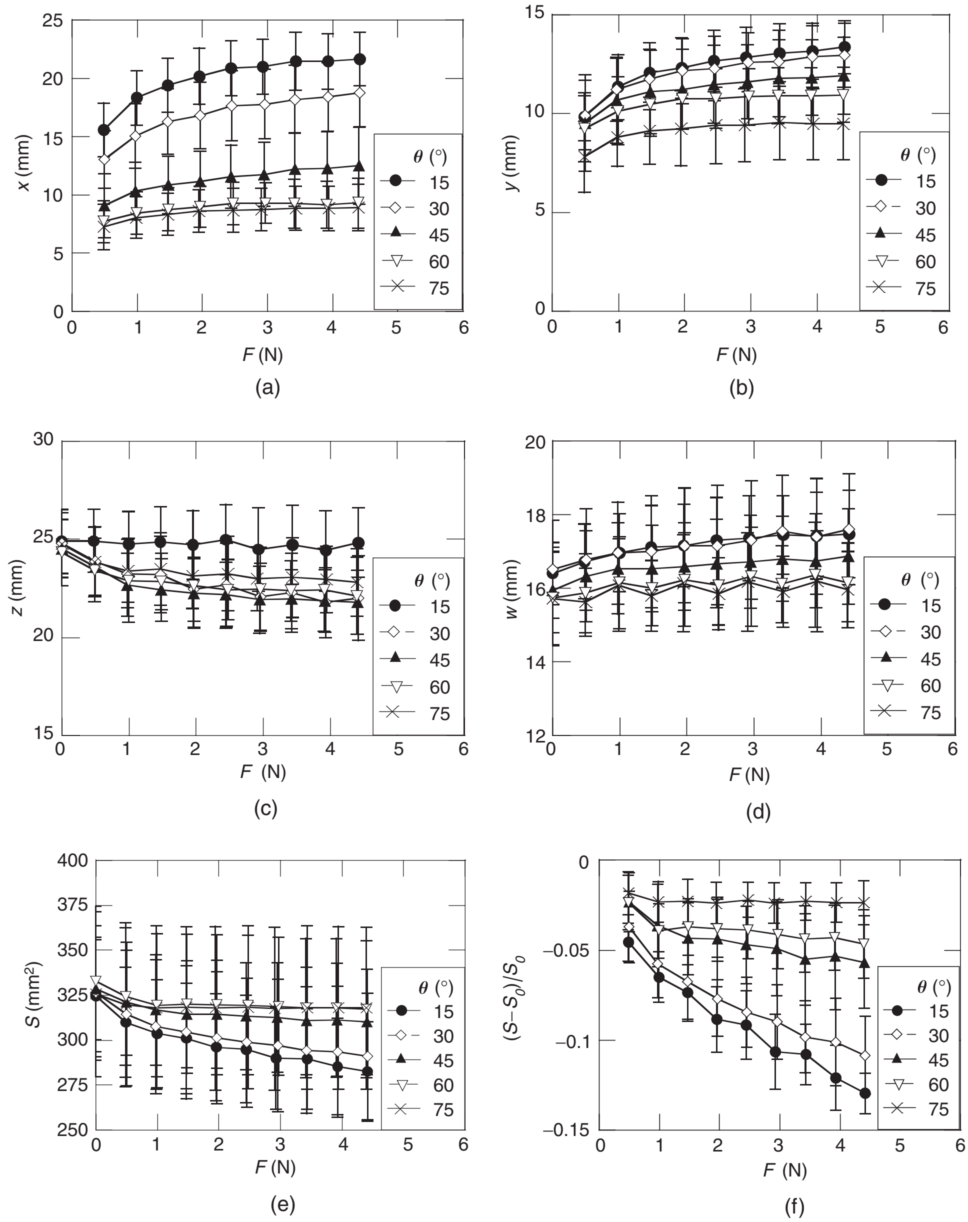

Figure 3 (a) Contact length (x) against the loading pressure F with the contact angle θ as a parameter dramatically increased at $F < 0.05$ N, increased less dramatically at $0.5\text{ N} < F < 3\text{ N}$, and was almost unchanged at $F > 3$ N, irrespective of F values. (b) Contact width (y) against the loading pressure F with the contact angle θ as a parameter sharply increased at $F < 0.05$ N, increased less dramatically at $0.5\text{ N} < F < 3\text{ N}$, and was almost unchanged at $F > 3$ N, irrespective of F values. (c) Length of the central axis (z) against the loading pressure F with the contact angle θ as a parameter was almost unchanged at $\theta = 15°$, irrespective of the changes in F. (d) Maximum width (w) against the loading pressure F with the contact angle θ as a parameter slightly increased at $\theta = 15°$ and $30°$ in parallel with the increase in F at less than 1.5 N. (e) Maximum area (S) against the loading pressure F with the contact angle θ as a parameter monotonously increased at $\theta = 15°$ and $30°$ in parallel with the increase in F. (f) In the distortion of the lateral-view area $(S - S_0)/S_0$ against the loading pressure F with the contact angle θ, the difference according to the contact angle was more remarkable and there was statistical difference between $\theta = 15°$ and $30°$ and $\theta = 75°$ and between $\theta = 15°$ and $\theta = 60°$ at $F = 1.5$–4.5 N.

there was a statistical difference between 15° and 75° of the contact angle at $F = 2.5$–4.5 N ($P < 0.01$). In addition, as the contact angle decreased, the increase in the contact width associated with the increase in the loading pressure became more pronounced.

The length of the central axis (*z*)

The length of the central axis (z) against the loading pressure F with the contact angle θ as a parameter was almost unchanged at $\theta = 15°$, irrespective of the changes in F

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(Fig. 3(c)). In cases with other θ values, z slightly decreased as F increased at $F < 3.0$ N. At $F > 3.0$ N, z was almost unchanged irrespective of the changes in F. There was no statistical difference between the groups with different θ values.

The maximum width (*w*)

The maximum width (w) against the loading pressure F with the contact angle θ as a parameter slightly increased at $\theta = 15^\circ$ and 30° in parallel with the increase in F at less than 1.5 N (Fig. 3(d)). However, w was almost unchanged at different θ and F, irrespective of the changes in F, and there was no statistical difference between the groups with different θ values.

The maximum area (*S*)

The maximum area (S) against the loading pressure F with the contact angle θ as the parameter linearly increased at $\theta = 15^\circ$ and 30° in parallel with the increase in F (Fig. 3(e)). However, S was almost unchanged at different θ at $F > 1.0$ N, irrespective of the changes in F. At all loading pressures, S at $\theta = 30^\circ$ tended to decrease more than S at $\theta = 15^\circ$, but there was no statistical difference in the average of S between the groups with different θ values.

Distortion of the lateral-view area $(S - S_0)/S_0$

The distortion of the lateral-view area $(S - S_0)/S_0$ against the loading pressure F with the contact angle θ as a parameter was shown in Figure 3(f). The difference according to the contact angle was more remarkable, and there was a statistical difference between $\theta = 15^\circ$ and 30° and $\theta = 75^\circ$ and between $\theta = 15^\circ$ and $\theta = 60^\circ$ at $F = 1.5$–4.5 N ($P < 0.01$), and as the contact angle decreased, the decrease in the distortion of the area due to the loading pressure became more pronounced.

DISCUSSION

Human fingertips are composed of the phalanx, nails, ligaments for flexor and extensor muscles, subcutaneous fat and skin, and each harbours elastic properties (Glicenstein and Dardour 1981). When a switch or button is pushed with the fingertip, the pulp of the fingertip comes in contact with the surface of the switch, transmitting pressure and the fingertip pulp changes shape as a result, thus increasing the area in contact with the switch (Wu *et al.* 2002). The major constituent of the fingertip pulp is subcutaneous fat. This tissue contains an abundant flow of blood, which is in continuous circulation that causes difficulty in simply calculating the dynamic properties of the elasticity of the tissue, and thus necessitates *in vivo* measurements in order to account for these factors (Silver *et al.* 2001).

Srinivasan *et al.* (1992) performed experiments in which the fingertips mechanically interacted with a cylinder filled with water, and measured the volume of the fingertips during the interaction. They found that the changes in the shape of the fingertips were not due to mechanical compression (Srinivasan *et al.* 1992). They also compared the undeformed and the deformed human and monkey skin surface under compressive load, and proposed new fingertips model that views the fingertip as an elastic membrane filled with an incompressible fluid under plane-strain condition. This model predicted the profiles of finger deformation well within 3 mm in the change of width of fingertip (Srinivasan 1989).

Serina *et al.* (1997, 1998) examined the changes in the frontal view of the fingertips when they were pressed, and found that the elasticity in the fingertips was primarily due to the presence of fat under mechanical loading pressures of less than 1 N, and the mechanical responses of the fingertips became smaller due to the hardness of the phalanx under pressures of more than 1 N (Srinivasan 1989; Serina *et al.* 1997). In addition, they produced a structural model of the forced compression of the fingertip with finite element, which consists of the skin and the subcutaneous tissue. The skin was modelled as an inflated, ellipsoidal membrane of 1-mm thickness, and the subcutaneous tissue was modelled in bulk as an incompressible and inviscid fluid. They showed that their model represented the experimental data sufficiently well, which suggested that geometry, inhomogeneous material structure and initial skin tension appear to represent the non-linear response of the *in vivo* human fingertip pulp under compression (Serina *et al.* 1998).

Wu *et al.* (2002, 2003) developed a two-dimensional non-linear finite element model of the fingertip, which was composed of soft tissue, bone and nail. In their model, soft tissue was assumed to be non-linearly viscoelastic, whereas bone and nail were considered to be linearly elastic. This model showed that the deformation of the fingertip under dynamic vibrating load was time dependent, and the duration of the tissue recovery depends on the rate of loading. They stated that the compressibility of the soft tissue was assumed to lie between that of hard tissue (e.g. bone, $v = 0.3$) and incompressible fluid ($v = 0.5$), and the soft tissue of fingertip remained mostly in compression under vibratory loading (Wu *et al.* 2002, 2003).

Data from this study demonstrated that as the contact angle became smaller, the increase in the rate of the contact length x and the contact width y became greater due to an increased loading pressure. When the shape of the contact area between the fingertip and the platform was approximated to be ellipsoidal in shape, the contact length and width corresponded to the longer diameter and the shorter diameter of the ellipse, respectively, and it was hypothesized that the increase in the rate of the contact area would increase as the contact angle decreased. When this result is reviewed in light of the anatomical structure of the fingertip as previously mentioned, the elasticity due to abundant fat tissue greatly changes its shape in response to the pressure in cases with small contact angles. On the other hand, in cases with large contact angles, tip of the nail receives a greater amount of pressure than the fingertip pulp. However, since this part of the fingertip contains less subcutaneous fat and the tip of the phalanx is closer to the skin, resulting in reduced elasticity, it is presumed that the mechanical responses to dynamic loading pressures are smaller.

Similarly, the lateral-view area demonstrated that as the contact angle decreased, the rate of decrease of the area due to increased loading pressure was larger, and this relationship became more visible by calculating the distortion of the area, representing the change from the basal value.

In contrast, no change was observed in the length of the central axis of the fingertip in relation to the contact angle. The tip of the central axis is included in the contact area initially when the contact angle is large. However, as mentioned earlier, since the area around the nail tip is near the phalanx and close to the skin and only small amounts of subcutaneous fat are present, little change was observed in response to altered loading pressure.

As Srinivasan *et al.* (1992) reported, if the volume of the fingertip is not influenced by the compressibility, the reduction in the area of the lateral-view in response to altered loading pressure is presumably compensated by the extension of the fingertip width, but in fact little change was observed. However, even considering these results, it is not possible to conclude that the fingertip may shrink. Rather, as the loading pressure increases, the whole fingertip extends along the central axis and vertically, and the mechanical responses may not be reflected in changes in the maximum width parameter. In clinical medicine, an index for the mechanical responses of the fingertip, as simple as possible, is preferred; however, it is suggested that three markers, including the contact length, the contact width and the lateral-view area within two-dimensional images, may be useful parameters to serve as this index.

On the basis of the anatomical structure of the fingertip, the amount of subcutaneous fat in the fingertip may be a critical factor in the mechanical responsiveness. At this point of view, the current results should be in addition compared with the parameters concerning to body size, including not only body height, weight, BMI and body fat ratio but also finger length and curvature radius of fingertip pulp.

CONCLUSIONS

1. The images of the mechanical responses were analysed when the fingertip was pressed against a plateau plate, and the influence of the contact angle on the loading pressure and the mechanical responses was investigated. Furthermore, with regard to clinical applications, useful parameters that indicate the mechanical responses of the fingertip were examined with the conveniently obtained dimensional images.
2. Results indicate that as the contact angle decreased, the ratios of change due to the loading pressure significantly increased with respect to the contact length, the contact width and the distortion of lateral-view area. These parameters were thought to be useful in clinical medicine as indices for the degree of mechanical responses of the fingertip.
3. The length of the central axis and the maximum width of the fingertip were inappropriate parameters to represent the mechanical responses of the fingertip. The maximum width of the fingertip changed very little. Thus, this parameter does not reflect the compressibility of the fingertip, and the fingertip as a whole extended along the central axis and in the vertical direction, and the change was not reflected in the maximum width.

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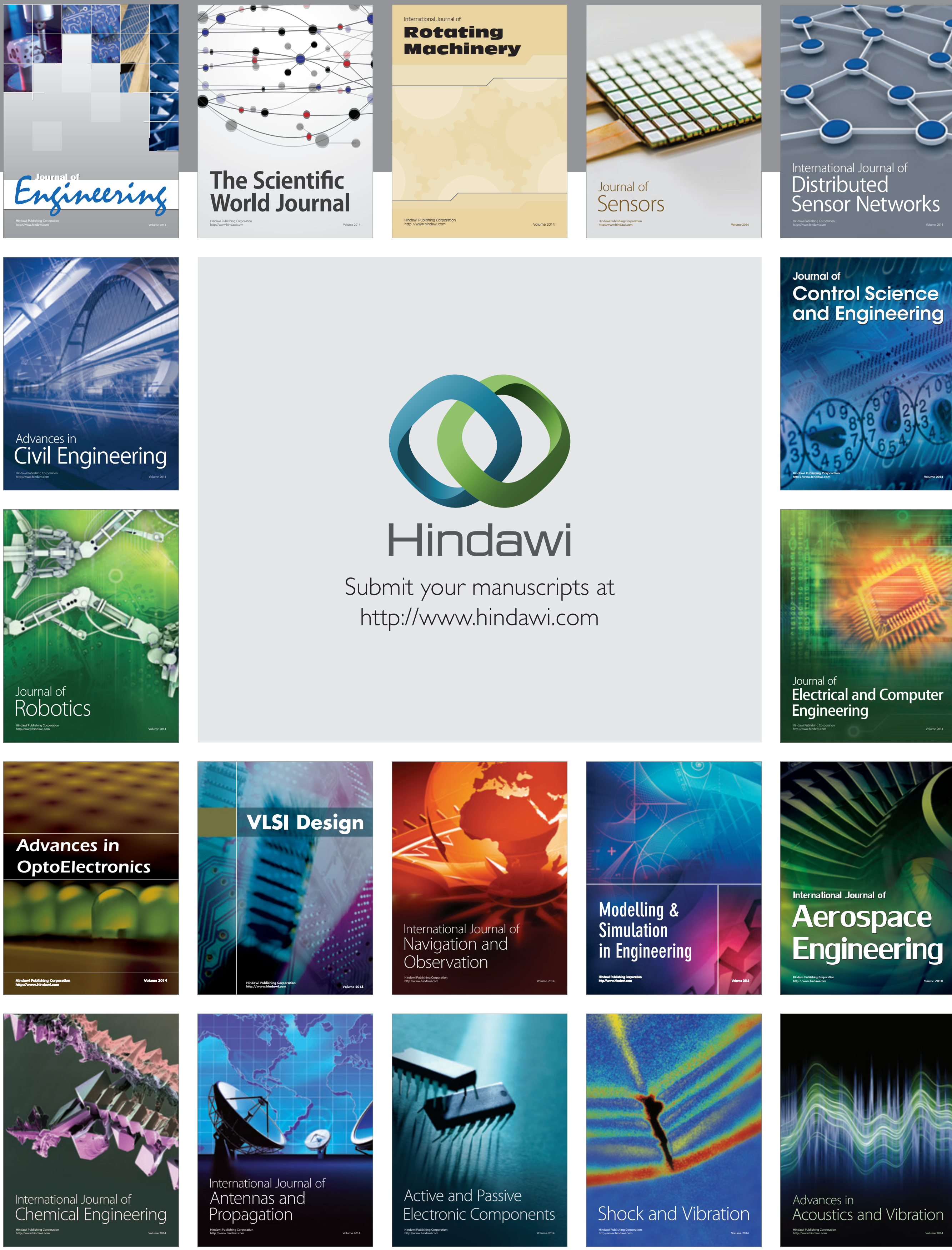
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