Understanding of Fingernail-Bone Interaction and Fingertip Hemodynamics for Fingernail Sensor Design

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Abstract

When the human fingertip is pressed against a surface or bent, the hemodynamic state of the fingertip is altered due to mechanical interactions between the fingernail and bone. Normal force, shear force, and finger extension/flexion all result in different patterns of blood volume beneath the fingernail. This phenomenon has been exploited in order to detect finger forces and finger posture by creating a photoplethysmograph "fingernail sensor," which measures the two-dimensional pattern of blood volume beneath the fingernail. In this paper, the anatomical structure of the fingertip is investigated in order to understand the various ways in which the bone and nail interact to alter the hemodynamic state of the fingertip. A qualitative nail-bone interaction model is created and used to explain the different blood volume patterns that result from each stimulus. The model is verified using experimental data from the fingernail sensor. The impact of this study on potential performance and application of the fingernail sensors is discussed.

1. Introduction

Fingertip forces play an increasing role in the fields of robotics, medicine, and virtual reality [1]. They act as bi-directional feedback between human and environment, either mechanical or virtual. Forces applied by a machine or virtual tool are fed back and presented to the human, while forces applied by the human are measured and fed back to the machine or virtual environment. Both application and measurement of fingerpad forces are required, and understanding the mechanics and dynamics of the human fingerpad is important for both.

Several researchers have investigated the mechanics and dynamics of the human fingerpad [2]-[5]. Resulting analyses lead to a better understanding of human grasping and manipulation, characterizations of the human haptic sense, ergonomic design criteria [2], and performance criteria for haptic feedback devices [6]. However only a few studies have taken into account the role of the fingernail in fingerpad behavior [7]. It is well documented in medical literature that the fingernail plays an important role in human grasping and fine manipulation [8], [9].

In addition to applying forces, the fingernail has recently been discovered to be useful for measurement of forces. When forces are applied to the fingerpad, interaction between the fingernail, bone, and tissue alters the hemodynamic state of the finger, creating various patterns of blood volume in the capillaries beneath the fingernail. In previous works, photoplethysmograph fingernail sensors have been designed which optically measure the two-dimension pattern of blood volume beneath the fingernail [10]. These patterns can then be used to predict the fingerpad forces. Normal forces, shear forces, and changes in finger posture have all been shown to result in different blood volume patterns.

In order to better design such fingernail force sensors, it is important to understand the sensing mechanism, including the mechanics of the fingernail-bone interaction and its effect on blood volume. In previous research, the mechanism behind the hemodynamic response to normal force has been quantitatively modeled, but the response to shear force and finger bending were not understood [11].

In this paper, a unified qualitative model will be created that will explain the mechanism behind the blood volume patterns for normal force, shear forces, and finger posture. First, the observable fingernail color patterns that are representative of blood volume are described. Next, relevant structural and vascular anatomy of the fingertip is analyzed and used to create the qualitative nail-bone interaction model. Experimental data from the fingernail sensor is then used to verify the blood volume patterns predicted by the model. Finally, the impact of this study on potential performance and application of the fingernail sensors is discussed.

2. Fingernail Color Patterns

As the human fingertip is pressed down on a surface with increasing force, the blood flow through the fingertip is affected, and a sequence of color changes is observed through the fingernail. In fact, the color change is characteristically non-uniform across the nail, resulting in distinct patterns of color change for different types of forces.

2.1. Normal Touch Force

Figure 1 shows the typical sequence of noticeable color changes with increasing normal force. As the touch force is first increased, the veins in the fingertip are collapsed, causing blood to pool up in the capillaries beneath the nail, resulting in the reddening effect. As the force continues to increase, the force propagates around the bone, collapsing the capillaries at the tip of the nail bed, resulting in a white zone at the tip of the nail.

Figure 2 shows an example of the effect of normal touch force on the fingernail. The pictures on the left show the fingernail coloration under ordinary conditions with no force. The pictures on the right show the coloration with normal force. Just as in Figure 1, the area around the bone is whitened, while the area above the bone is reddened. Digital filtering techniques are used to improve the contrast between red and white zones. In the figures on top, the contrast has been multiplied by five, and in the figures on the bottom, an intensity threshold has been applied.

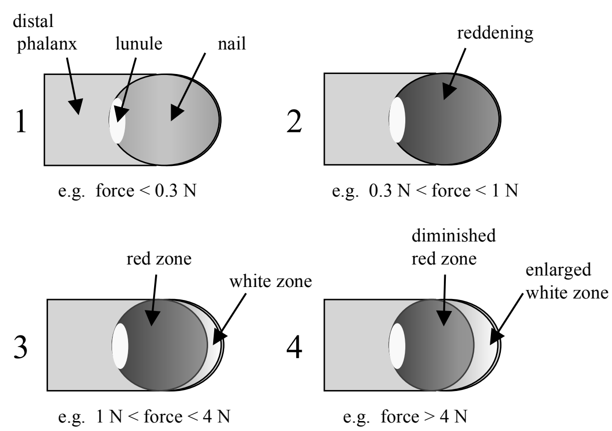

Figure 1. Fingernail colors due to touching.

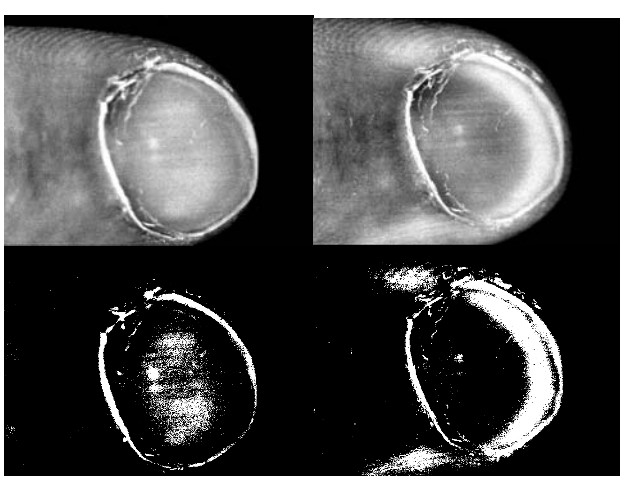

Figure 2. Visible effect of normal touch.

2.2. Change in Posture

Normal touch force is not the only action that results in a change in fingernail color. When the posture of the finger is altered, i.e. the joints of the finger are bent or extended, the color of the finger changes as shown in Figure 3. When the finger is extended, a tension is set up in the tissues of the nail bed that collapses the capillaries. When the finger is bent, that tension is relieved and the capillaries fill with blood again. The color changes shown in Figure 3 are concentrated near the center of the nail, whereas the color changes due to normal touching occur particularly towards the tip of the nail. Therefore it should be possible to distinguish between a touching action and a change in finger posture based on observable changes in fingernail color patterns.

Figure 4 demonstrates the visible effect of finger extension on the fingernail. When the finger is extended, whitening occurs between the bone and the fingernail, especially at the distal end of the bone. When the finger is flexed, the whitening disappears and the entire nail reddens.

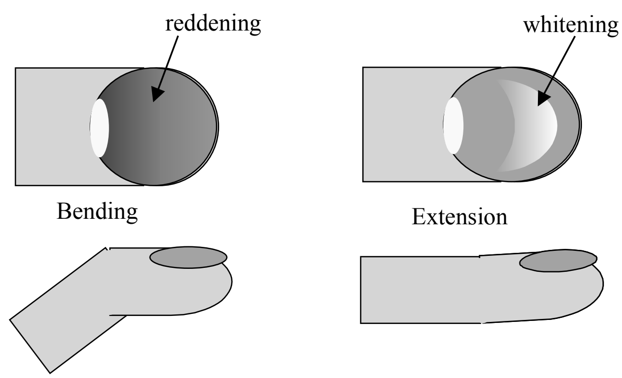

Figure 3. Fingernail colors due to bending.

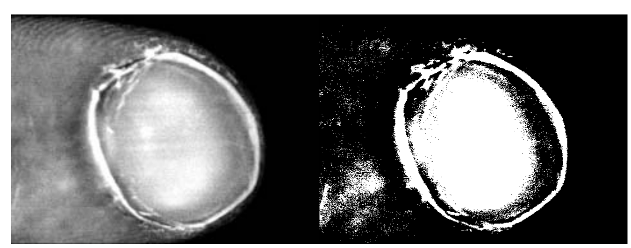

Figure 4. Visible effect of extension.

2.3. Shear Force

When shear forces are applied to the palmar surface of the fingertip, yet another set of color patterns result, as shown in Figure 5. If the shear force is applied longitudinally, a tension in the tissues of the nail bed is set up, resulting in either a broad whitening effect over the center of the nail or a white band at the tip of the nail, depending on the direction. If the shear force is applied laterally, tension in the nail bed creates whitening zones that are asymmetrical.

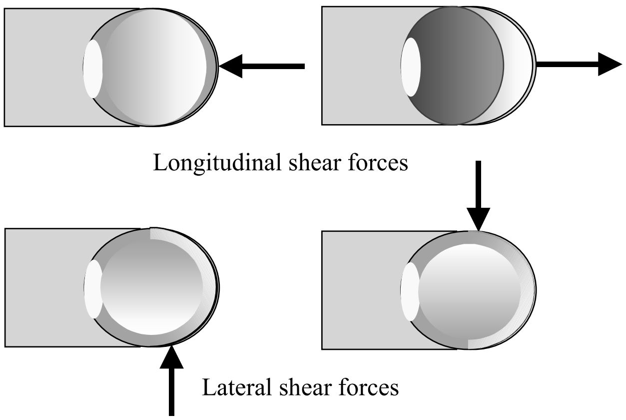

Figure 5. Fingernail colors due to shear.

Figure 6 depicts the visible effect of lateral shear force on the fingernail. In the picture on the left, the shear force is applied from top to bottom, while on the right, the shear force is applied from bottom to top. In both cases, the fingernail whitens around the bone on the far side of the nail toward which the shear vector is pointing, as well as over the bone toward the near side of the shear vector.

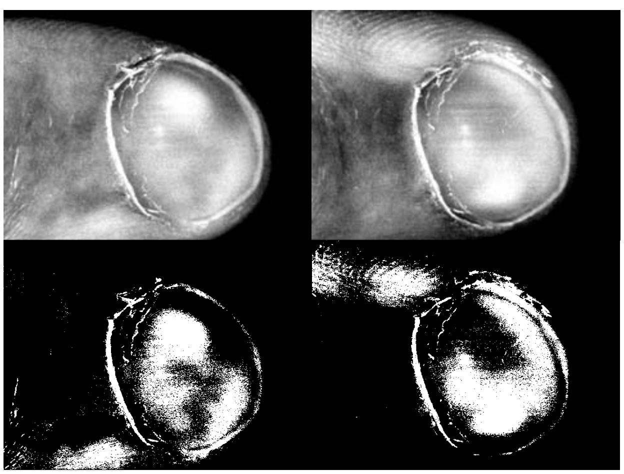

Figure 6. Visible effect of lateral shear force.

Finally, Figure 7 shows the visible effects of longitudinal shear force. The picture on the left depicts shear applied to the finger from left to right (positive by our convention). In this case we see whitening over the bone, but reddening at the tip. The picture on the right depicts shear applied to the finger from right to left (negative by our convention). In this case, we see whitening around the bone, which is not significantly different from the patterns caused by normal force alone.

Since the patterns for lateral shear force are distinctly asymmetrical, it should be easy to distinguish from normal touching and bending. However, longitudinal shear forces may present a greater challenge to distinguish. When the longitudinal shear is applied inward (top right of figure), the whitening zone is similar to that of bending, but extends all the way to the lateral edges of the nail. When the longitudinal shear force is applied outward (top left of figure), the whitening zone is almost indistinguishable from that of normal touching, making this perhaps the most challenging force to measure. However, there may be subtle variations in blood volume that are more visible to optoelectronic sensors than to the naked eye.

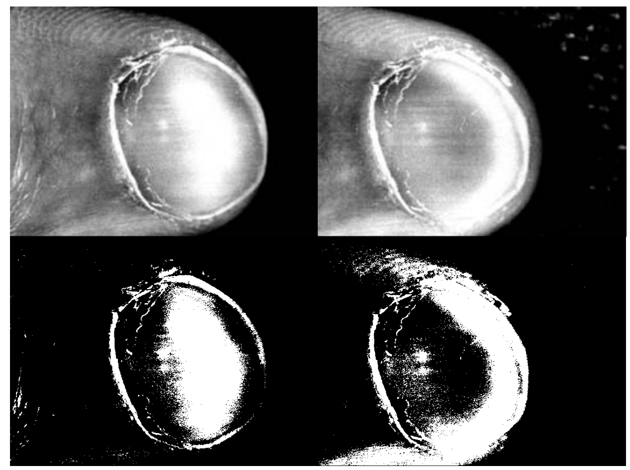

Figure 7. Visible effect of longitudinal shear.

3. Anatomy of Fingertip and Nail Bed

In order to explain the mechanism behind the changes in color of the fingernail, it is necessary to thoroughly understand the relevant anatomy and physiology of the fingertip. First, the anatomical structure and function of the fingertip and fingernail is investigated. Secondly, the blood flow in the fingertip and fingernail bed will be investigated.

3.1. Structure of the Fingertip and Fingernail

Details of the anatomical structure of the fingertip can be found in several references such as [8], [9], [12]. The top portion of Figure 8 shows a saggital cross-section of the fingertip. The bone of the distal phalanx is surrounded beneath by the soft deformable tissue of the pulp and above by the nail unit. The nail plate is attached to the bone by the anterior ligament (AL), the posterior ligament (PL), and the bed mesenchyme (BM), the latter having an almost ligamentary or tendon-like character [8]. This anchoring serves to maintain the positional relationships and distances between the matrix, bed, hyponychium, and bone, which are critical for nail health and functionality. The nail plate is generated by the matrix, grows up and emerges out from under the proximal nail fold at the eponychium, curves over the nail bed, and separates from the fingertip at the hyponychium. It is transparent and colorless, acting as a window into the nail bed.

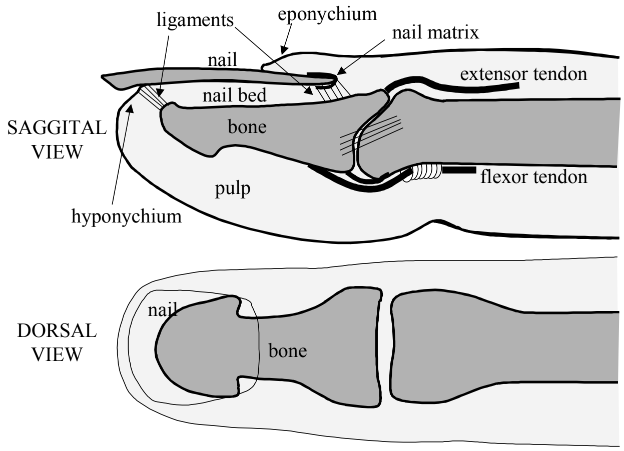

Figure 8. Structural anatomy of the fingertip.

Figure 8 also shows the actuation mechanism of the fingertip. Movement of the finger and forces at the fingertip are effected by means of a network of flexor and extensor tendons, [9]. The extensor tendons pull the finger up into an extended position, while the flexor tendons pull the finger down into a bent or flexed position.

3.2. Blood Supply of the Fingertip and Nail Bed

According to [8], after application of pressure to the pulp, this middle nail bed turns pinker while the distal bed becomes whiter, which supports the role of the bed vasculature as the main source of the pink color of the bed.

A variety of details on the vascular anatomy of the fingertip can be found in several sources such as [8],[9],[13]-[16]. The nail bed is richly vascularized with blood flowing from the digital arteries into a network of arterioles, through capillary loops just under the surface, and back out through the venules to the digital veins. Figure 9 shows a diagram of the principal arteries and veins. The main digital arteries divide into a network of smaller arteries that run principally above the bone, which is connected to the fingernail via a strong matrix of collagen and elastic fibers, as described in the previous section. As a result, the arteries underneath the nail are protected from touch pressure, allowing uninterrupted supply of blood to the capillaries under the nail. However, the flow of blood out of the fingertip relies largely on the lateral ramifications of the digital veins shown in the figure [16]. In addition, the veins are generally larger and more compliant than the arteries, leaving them susceptible to collapse by touch pressure. As a result, when touch pressure is applied to the fingertip, the veins are collapsed, causing blood to pool up in the capillaries underneath the nail.

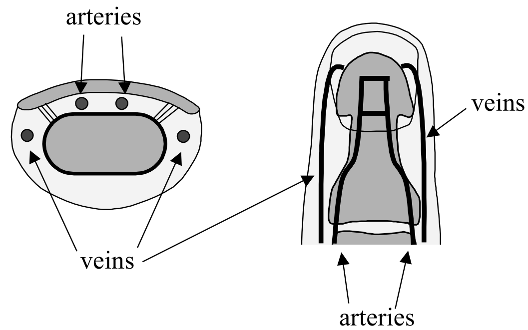

Figure 9: Vascular anatomy of the fingertip.

The capillaries run longitudinally under the nail bed and are twice as long and twice as numerous as those in the pulp on the palmar side of the fingertip [13]. Under normal conditions, the blood in the capillaries is rich in oxygen and therefore red. Thus the blood that pools up in the capillaries of the nail bed is highly visible and is responsible for the reddening effect described earlier. However the capillaries under the nail at the tip of the finger are not protected by the bone. Thus touch pressure can propagate around the tip of the bone, causing these capillaries to collapse and pushing all of the blood out of them. This results in the whitening effect described earlier.

A final relevant detail is that the arteries are tortuous and coiled while the veins are not [15]. Thus when the finger is bent, the veins become kinked, while the arteries merely uncoil.

4. Fingernail-Bone Interaction Model

4.1. Basic Mechanism

As described in the previous section, and shown in Figure 8, the fingernail is connected to the bone of the distal phalanx by a matrix of strong fibers, especially around the perimeter of the nail, which prevent the nail from detaching from the bone, even under very high tension. However these fibers do not prevent the nail from being compressed against the bone. Touch forces and posture are maintained through tension in the flexor and extensor tendons, which are attached at the proximal end of the bone. The tendons are thus able to exert torque on the bone but do not directly affect tension in the tissue of the fingertip.

The bone itself has a distinctive arrowhead shape with protuberances at both ends where the fibers are attached. The bone does not extend all the way to the hyponychium where the nail detaches from the skin. This geometry is important in determining the regions of the nail bed that are affected by various forces within the fingertip. The shape and position of the bone and its effect on the nail bed capillaries is evidenced by Figure 10. On the left, the finger is pressed down against a flat surface. The profile of the bone is visible as the region of red where the capillaries are protected from collapsing due to the pressure. On the right, the nail is pressed against a transparent surface. In this case the profile of the bone is visible as the region of white where the capillaries between the nail and bone are compressed and collapsed, which also confirms the inability of the nail fibers to support compression.

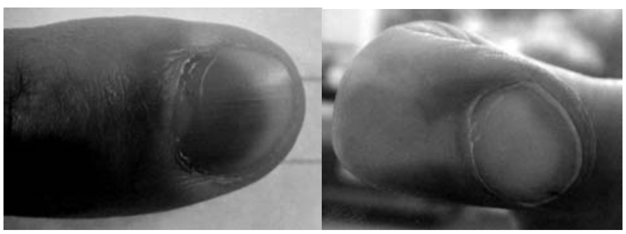

Figure 10. Nail-bone interaction.

The important characteristics of the basic bone-nail interaction model can be summarized as the following:

- The bone (distal phalanx) has a distinctive arrowhead shape with protuberances at both ends.
- The fiber matrices between nail and bone support tension but not compression.
- Tension in the tissue allows blood volume to increase while compression causes blood volume to decrease

This basic model is now ready to be applied to explain the mechanism behind each of the various types of touch force and posture.

4.2. Normal Force

Figure 11 depicts the nail-bone interaction and its hemodynamic effect for normal force. The top diagrams depict the ordinary state of the fingertip when no force is applied. The tissue is shaded lightly to indicate it is neither in tension nor compression. The transverse and dorsal views also depict the primary arteries (over the bone) and veins (beside the bone). The bottom diagrams show a z-force exerted beneath the fingertip and its corresponding reaction force exerted by the bone, which is achieved by tension in the flexor tendon. These forces compress the tissue of the pulp between the bone and the surface, as depicted by the area in white. Note that the compression extends to the area around the bone as well as beneath it. This is because the nail bed fibers are in tension and pull the nail down with the bone, compressing all the tissue that is around the bone but beneath the nail. This includes the lateral aspects of the finger where the primary veins lie. Thus the veins are collapsed, causing blood to pool up in the protected capillaries between the nail and the bone, as depicted by the area shaded darkly.

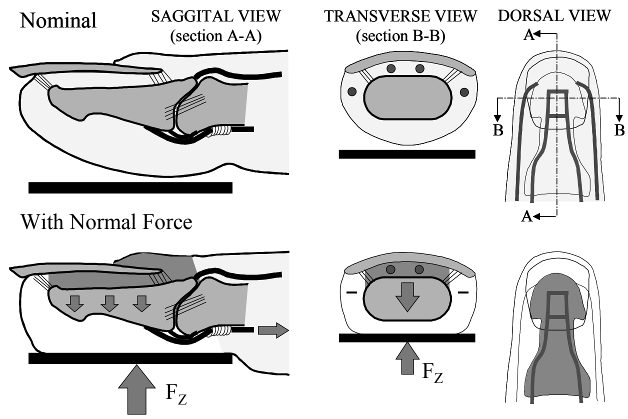

Figure 11. Normal touch mechanism.

4.3. Extension/Flexion

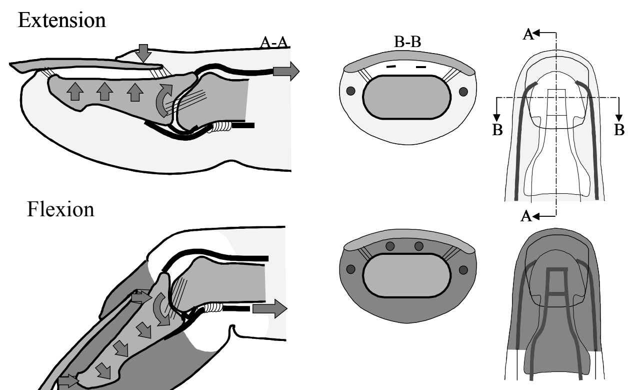

Figure 12. Bending mechanism.

Figure 12 depicts the nail-bone interaction and its hemodynamic effect for finger extension and flexion. During extension, the extensor tendon pulls the bone upward against the fingernail, which is held in place by a reaction force from the proximal nail fold. Since the fibers of the nail bed do not support compression, the capillaries are collapsed between the bone and the nail, especially above the bony protuberance at the distal end of the bone.

When the finger is flexed, the flexor tendon pulls the bone down away from the nail, relieving the compression between the nail and bone. Since the nail bed fibers are now in tension, the fingernail maintains a normal position relative to the bone. However, additional reddening occurs throughout the fingertip since flexion of the finger kinks the veins, causing blood to pool up in the capillaries throughout the fingertip.

4.4. Lateral Shear Force

In the case of lateral shear force, the bone-nail interaction is more complex, as depicted in Figure 13. In order to apply shear, a normal force must be simultaneously exerted in order to allow for friction. It has already been established that when normal force is applied, the area around the bone is compressed and whitened. When lateral force is exerted in addition to normal force, a lateral reaction force is maintained in the bone by the ligaments of the joint, and the tissue of the pulp between the bone and surface experiences a shear force that pulls the tissue toward the far side of the shear vector. Thus the tissue at the far side becomes bunched up around the nail due to shear and whitened due to compression by the normal force. However, on the near side of the shear vector, the tissue is pulled away from the nail by the shear force. The tension of this pulling action prevents compression of the tissue at the near side, resulting in reddening. Furthermore, the tension at the near side pulls the nail down on top of the bone there resulting in whitening.

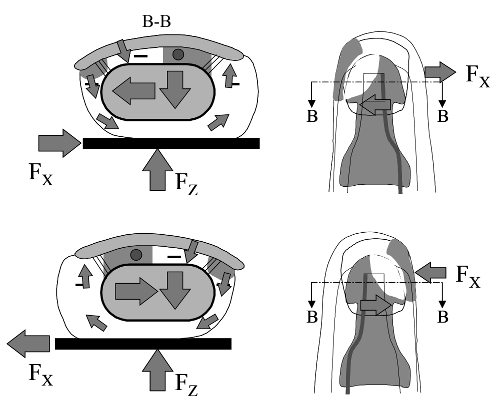

Figure 13. Lateral shear mechanism.

4.5. Longitudinal Shear Force

Unlike lateral shear force, the mechanism of longitudinal shear force is different for positive and negative forces, as depicted in Figure 14. When force is applied in the positive direction, as depicted in the bottom diagrams, the mechanism is similar to lateral shear. Applied shear and reaction force in the bone pulls the tissue proximally. At the distal end of the nail, the tissue is pulled away, generating tension and preventing the capillaries from collapsing, resulting in reddening. However the tension pulls the nail down on top of the bone, generating a whitening zone between the nail and bone. When force is applied in the negative direction, as depicted in the top diagrams, the tissue is bunched up at the distal end of the nail due to the shear and compressed due to normal force.

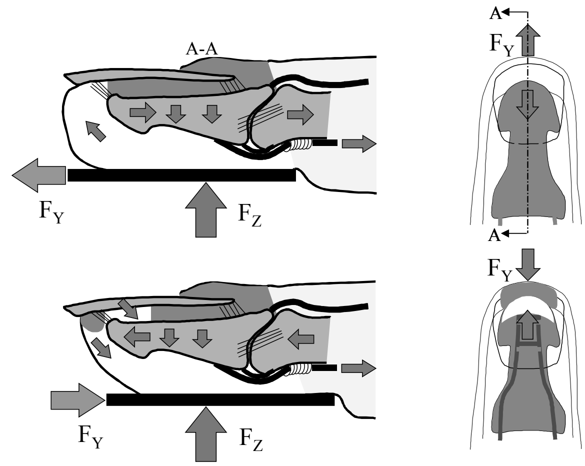

Figure 14. Longitudinal shear mechanism.

5. Verification and Applications

5.1. Experimental Verification

In order to verify that the blood volume patterns predicted by the nail-bone interaction model are accurate, experimental data is collected using the fingernail sensor developed in previous work [10]. Figure 15 shows the arrangement of the optical components of the fingernail sensor. There are eight photodiodes in a two-dimensional array with six LEDs in between. The signal from each photodiode is dominated by the local blood volume beneath the fingernail.

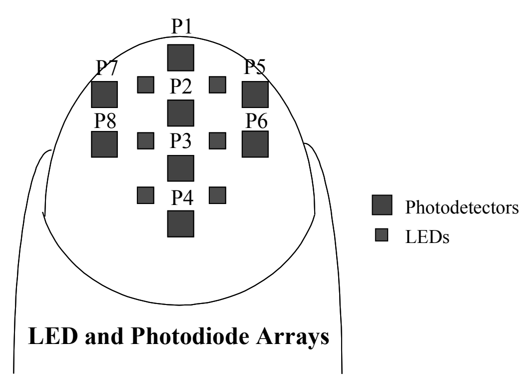

Figure 15. Sensor arrangement.

Figure 16 to Figure 19 show the responses of the eight photodiodes to normal force, bending, lateral shear force, and longitudinal shear force. In each figure, the eight plots are arranged in the same formation as the photodiodes on the fingernail. In each case, the human subject was asked to slowly vary the stimuli of interest over several cycles while holding the others constant. The photodiode signals are plotted vs. the applied stimuli. The forces are measured using a three-axis force sensor and the joint angle is measured using a video camera. The hysteresis in each of the curves is due in part to the fact that the other three stimuli are not held perfectly constant while the stimuli of interest is being varied.

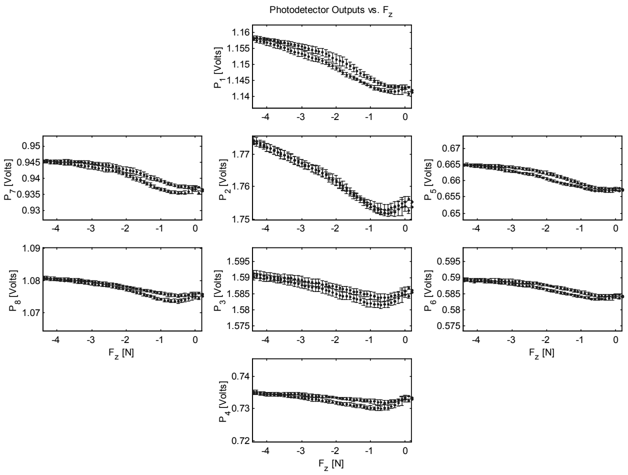

Figure 16. Sensor response to normal force.

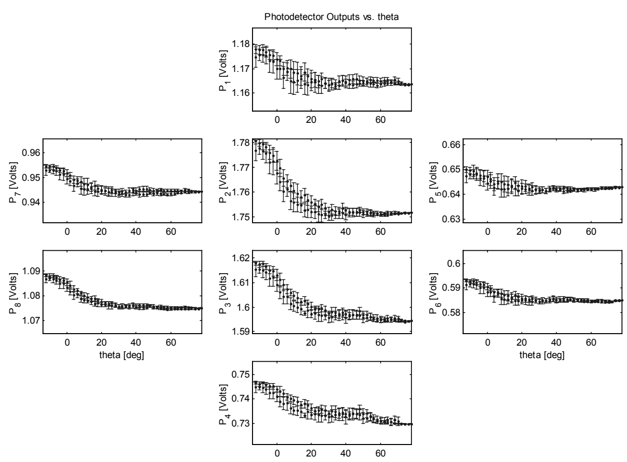

Figure 17. Sensor response to extension/flexion.

When the magnitude of normal force increases, the photodiode signals increase, particularly towards the front and sides of the fingernail. This is because the whitening causes more light to be reflected, increasing the photodiode response. The front-most photodiode levels off first because it is the first to go completely white. As more force is applied, the white zone grows proximally and the middle photodiodes continue to increase.

When the finger is flexed (increasing joint angle), the middle of the nail is reddened and the photodiode signals decrease, particularly in the middle of the nail. For extension, the nail whitens and the signals increase.

When lateral shear is applied, the photodiodes now act in a laterally asymmetric pattern as expected. For positive lateral shear (i.e. shear applied from right to left), the distal right side reddens (decreasing signal) and the distal left side whitens (increasing signal), just as predicted by the model. Likewise, for negative lateral shear (left to right), the distal left side reddens and the distal right side whitens. The photodiode at the front middle stays whitened, while the photodiodes in the rear fluctuate as the proximal whitening zone shifts around over the bone.

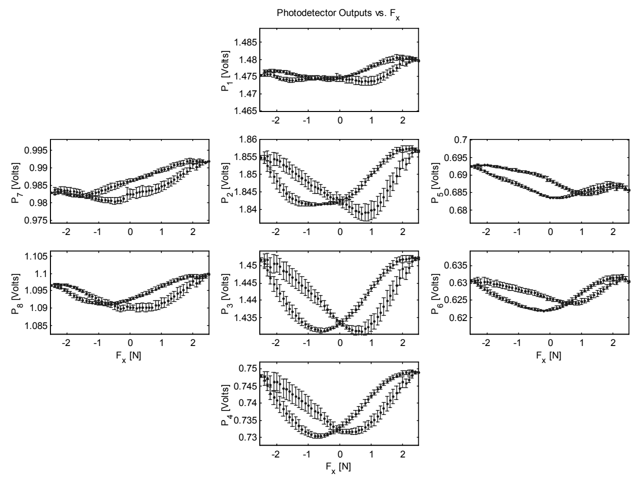

Figure 18. Sensor response to lateral shear.

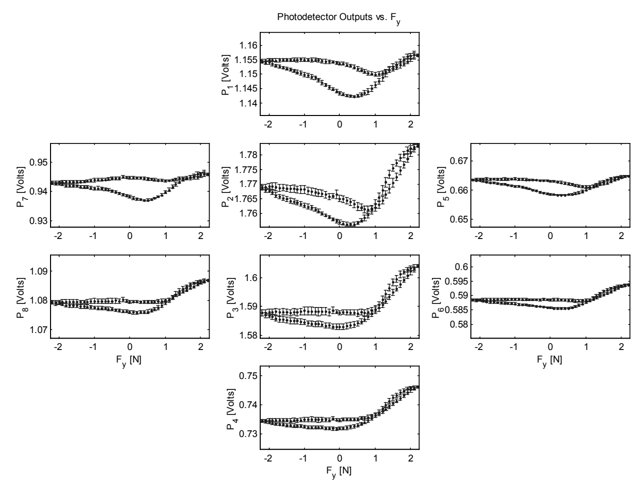

Figure 19. Sensor response to long. shear.

When longitudinal shear is applied in the positive direction (front to back), the photodiodes signals all increase due to the broad whitening zone in the middle of the nail. However, when longitudinal shear is applied in the negative direction (back to front), the photodiode signals tend to remain the same or increase only slightly. Thus negative longitudinal shear will be difficult to distinguish based on sensor readings.

5.2. Impact on Applications of Fingernail Sensor

Since the fingernail sensor is capable of measuring shear force in addition to normal force, a potential application is to use the fingernail sensor as a wearable computer mouse, as shown in Figure 20. This is especially feasible since the sensors are most sensitive in the range of 0 to 2 N, which is comfortable for a human to apply on a continuous basis.

However, because both the model and experimental evidence suggest that negative longitudinal shear may be difficult to detect, the wearable mouse application should be designed to function based only on normal force, lateral shear, and positive longitudinal shear. It is possible that the two axes of cursor motion could be controlled by lateral shear and some combination of normal force and longitudinal shear. If the human presses the finger against the side of the computer monitor, then predicted normal force could be intuitively used to control horizontal cursor position, while predicted lateral shear force could be used to control vertical cursor position. Clicking would be achieved by dynamic tapping or by using a second finger.

Figure 20. Wearable mouse application.

6. Conclusions

In conclusion, this paper developed a unified qualitative model that explains the fingernail-bone interaction and resulting blood volume patterns that occur in the fingernail bed when various forces and changes in posture are applied to the fingertip. This model is useful in understanding the measurements obtained using the fingernail sensor and designing sensor applications. Using the model, the sensor could be redesigned with an optimal configuration of photodiodes for distinguishing the various patterns of blood volume resulting from normal force, finger bending, lateral shear force, and longitudinal shear force. The understanding of the nail-bone interaction should also prove to be useful for understanding human grasping and manipulation. In future work, a quantitative model of the nail-bone interaction will be developed.

Acknowledgement

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