

École polytechnique de Louvain

Fingerpad deformation during robot-controlled tactile stimulation

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Chapter 1

Introduction

The hand is maybe the most versatile limb of our body. Flexible, agile, his coordinated fingers allow human beings to design the most amazing creations, so far unequalled in the animal kingdom. Hand function requires interaction of muscles, bones, joints, nerves and tendons. It provides a wide range of functions such as creation of course, but also manipulation, communication, sense of touch and grip strength. Loss or deterioration of hand is a tragic event. For millennia, humans have tried to recreate limbs for injured people. Today, it exists many different models more or less sophisticated. However, despite of undeniable progress, hand is far from being fully understood. Indeed, a dexterous manipulation requires the ability to handle objects without slippage and dropping of the object. A safely held object in hand means an appropriate amount of force applied on its surface, to counteract slipping. This force should be large enough to hold an object, but not too large neither to avoid to damage it or to deploy too much energy unnecessarily. Nevertheless, how to evaluate this force ? To answer this question, we need to study fingertip skin deformation, external objects interactions and how they are translated to tactile information. In other words, we need to understand the biomechanics of both the skin and subcutaneous tissue of the fingers and how the neural system reacts to it. The topic of this thesis is to present methods to study how the finger pad is deformed under shearing, from a front point of view. The long run objective is to collect data to validate finite elements simulations, in order to better understand the fingertip biomechanics.

Before getting to the heart of the matter, let's provide some general background information. We know that human beings can evaluate grip states thanks partly to slips appearing on fingertips pressed against a handled object. [3]. We believe that the friction of an object may not be encoded per se, but may trigger short and localized slip events that imply impending slip. There is indeed evidence that small, short-lasting slips occur during manipulation [13]. Those slips are not instantaneous but develop progressively, trigger strong afferent responses and elicit grip force adjustments [12, 9]. Thus, when an object starts to slip away from fingers, partial slips occurs in the fingerprint until complete slippage. Figure 1.1 shows, the typical evolution of the fingerprint contact from the initial contact to full slip. First 'incipient' slips occurs at the periphery of the contact and an annulus of slip forms around a remaining 'stuck' zone. This former represents the area where the skin remains fixed and is not affected by the global slipping. Out of the zone, we observe an homogeneous slipping. This stuck zone totally disappears once the slip is total [2]. During the slipping, tactile mechanoreceptors embedded in the fingertip respond to those stresses and strains with action potentials [10, 11, 16, 20]. Resulting afferent signals allow the brain to trigger specific actions such as grip force adjustments or to extract information about the object (texture, shape...). Fingertip humidity plays a critical role too. It has been shown that since humid skin is more flexible than dry skin [1], the global deformation dynamic is faster with a dry skin. This makes the slip detection task harder [2]. Skin hydration depends on both physiological and environmental conditions [15, 1]

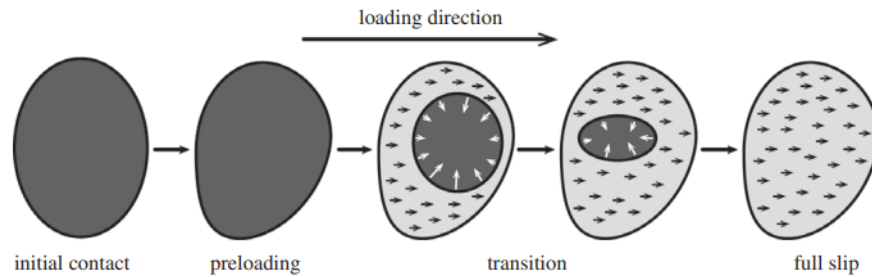


Figure 1.1: Course of evolution of the dynamics of finger contact from the initial contact to full slip. From left to right: initial stuck contact (dark grey), preloading, slip onset starting at the trailing edge, growth of the slip region (light grey), full slip. Figure from [2].

We previously announced that a current solution to study the finger pad biomechanics as a whole and how deformations allow the brain to evaluate grip state, given its complexity, is to run simulations on the finger pad thanks to finite elements methods FEM. To validate the model, we need to collect data about the finger pad. Indeed, this former has a complex structure and its properties analysis require a large number of free parameters, to describe its geometry and mechanics with high accuracy (e.g. skin thickness and elasticity) [7]. Once the biomechanics known, the utter objective would be to further study how deformation and afferent signals are linked to provide the brain information about grip state.

In order to measure stresses and strains in the fingertip skin resulting from a given stimulus and to model skin properties, several attempts have already been made. Most of these studies focus on the normal loading of the finger. Outcoming results show that fingertip geometry has a large effect on stress distribution and intensity [19]. Indeed, mechanoreceptors are not all placed at the same points and thus don't react the same way to a global stimulus. Studies about tangential loadings have also been made and allowed to collect more data about fingertip deformation under tangential and normal stresses [7]. In this latter, the fingertip rests on a robotic plate that moves in different directions with different speeds and with different normal forces. Figure 1.2 illustrates the used experimental apparatus. Those studies show that deformation fit in many way homogeneous elastic models, but this latter remain insufficient to explain some results such as deformation dependence on stimuli directions. Indeed, fingertip is neither homogeneous, nor spheric, nor isotropic as supposed by models. Higher accuracy predictions have been obtained thanks to finite-element model simulations (FEM) based on multi-layered skin [6, 21]. Hence the interest of this method.

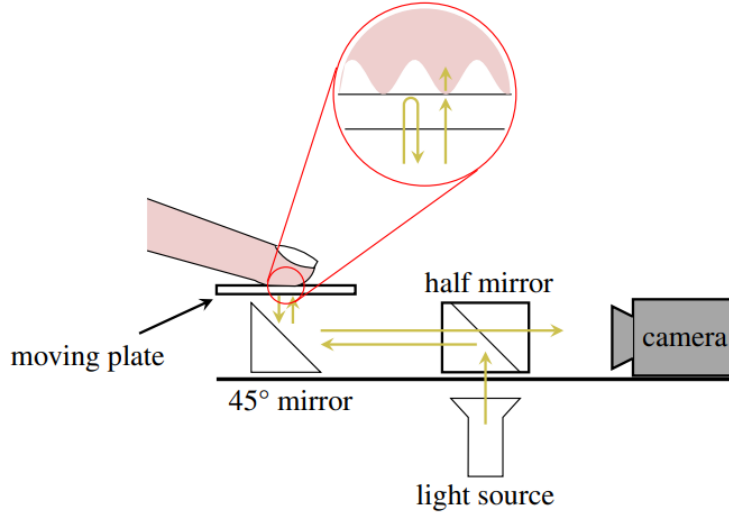


Figure 1.2: Apparatus used for the experiment to study strains in the fingerprint under shearing. Subject’s hand rests in the hand support, with the right index finger fixed. The robotic smooth transparent plate translates precisely in 4 different directions. The imaging system that films deformations in the fingertip comprises a camera, a half mirror, a full mirror and a light source. Figure and note from [8].

Those studies [9, 3, 7, 8] focused on the fingerprint deformation. However, as said before, in order to validate finite elements simulations FEM, we need to collect large amounts of data from the fingertip as a whole. So far, we have collected data about the fingerprint but finger pad deformation on lateral and front sides have not been investigated yet, as far as we know. Those data are crucial to validate FEM simulations. Therefore, in this paper, we will expose methods to collect those data as well as some results obtained thanks to them. We will conduct experiments on the finger under normal and tangential loadings and apply tracking algorithms in order to track features to study how the finger deforms when pressed against a robot-controlled plate. We are interested in strains, evolution of the visible bulk area and the contact length with the robotic plate. To do so, we use a dedicated custom robotic platform, similar to the one illustrated in figure 1.2. We image the fingertip deformation when pressed on a flat surface and we execute tangential sliding movements in four different directions, with three different normal forces and at a particular speed. Figure 1.3 provides an illustration of the setup. Once data are collected, we run our tracking algorithm to track deformation in the fingertip. In addition to the results, we also expose the reliability of this method as well as its limitations. Indeed, imaging skin deformation from a lateral and front point of view assumes an important hypothesis : deformation in a two-dimensional plane. Of course, this statement is not true. The fingertip is a 3D structure and

this hypothesis can lead to uncertainty that we will evaluate.

In a first time, we describe the experimental protocol, then our study methodology as well as the used algorithms to track deformation. Thereafter, we explain the underlying used principles and show the limits of our methods. We expose after our results discuss them. Finally, we conclude on our discoveries about fingertip deformation and how we could solve the limitations encountered.

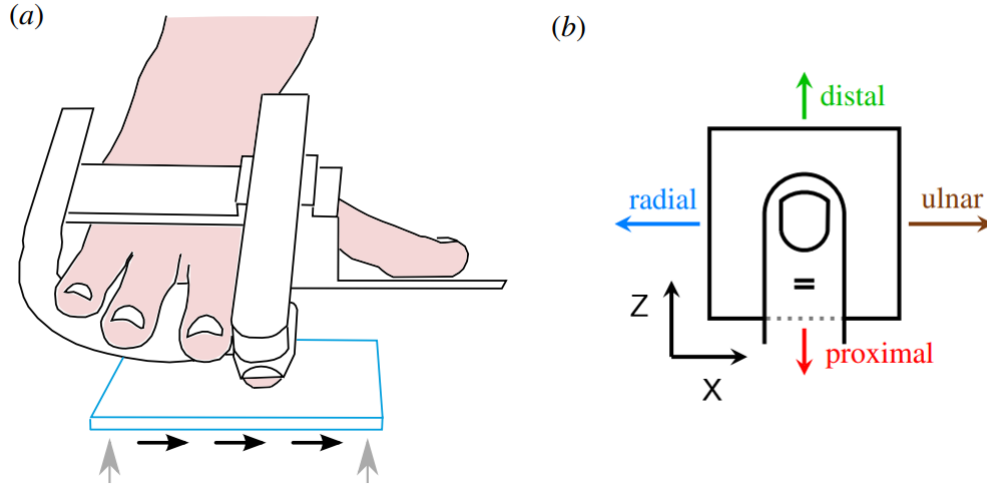


Figure 1.3: (a) Experimental apparatus. The horizontal glass plate moves by means of a robot actuator. The plate loads on the finger (servoed normal force) and moves sufficiently far such that the finger is completely sliding in one of four directions with position control. (b) Stimulus directions: directions correspond to the movement of the glass plate relative to the fixed finger. ‘Radial’ is towards the thumb side of the hand and ‘proximal’ is towards the wrist. Image and note from [7].

Chapter 2

Materials and Methods

2.1 Data Collection

2.1.1 Apparatus

We use an apparatus very similar to the one used in the paper [8] and introduced in the introduction in figure 1.2 . We rewrite it down here in details for clarity and to present what changed with previous setups. In order to control stimuli to the finger pad, a full custom robotic platform was developed. The platform is based on an industrial four-axis robot (DENSO HS4535G) that can translate in three orthogonal directions. Its position is servo-controlled with a position resolution of $15\text{ }\mu\text{m}$ by a factory controller with a frequency of 1 kHz. The subject's index finger is fixed in a support that maintains a constant angle, around 20° , between the finger and the stimulus, which is a typical angle adopted during grasping and tactile exploration. This small angle makes the distal phalanx nearly parallel to the surface [4]. The subject's nail is guided by a fixed piece of rigid plastic, which approximately has the same curvature as the nail. It is also hooked distally to block the nail position. The subject rests his fingertip on a moving plate and his arm on a support.

The surface in contact with the index fingertip, called the stimulus, is a smooth plate made of a transparent glass. The stimulus is fixed to the end-effector of the robot. A force transducer (ATI Nano43) measures the normal force applied to the finger pad during the experiment. This transducer has a 18 N range and 0.004 N resolution. Besides, a data acquisition board (NI PCI 6225) acquires the force signals at 1 kHz frequency. A proportional-integral-derivative (PID) controller feeds back the normal force in order to keep a constant normal force tuned at the desired magnitude. This setup allows to apply stimuli to the fingertip to recreate what it undergoes under loading and shearing.

Since tracking performance require good lighting, three light sources equip the setup. The first one comes from the bottom and goes through the robotic transparent plate. This light was already present in the previous setups. The second light source is a torch placed above the setup, to provide a lighting from the top right (with respect to the subject). Finally, a small LED, attached to the hand support, was added next to the finger. This LED provides a lighting from the top left (with respect to the subject). Both light sources have been added for this work. An illustration of the setup is given in figures 2.1 and 2.3. Figure 2.2 shows the apparatus from a different point of view in order to make the LED visible.

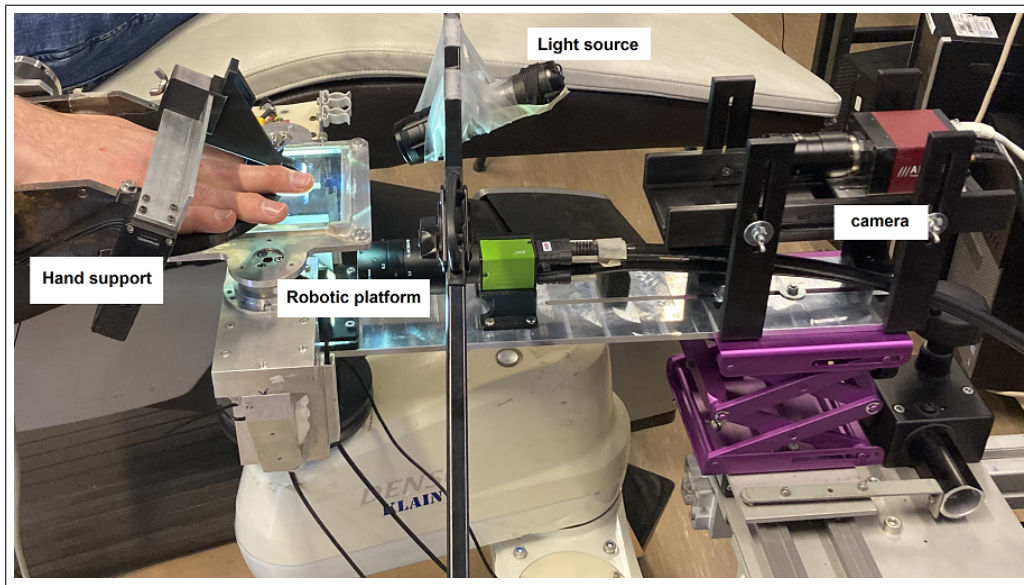


Figure 2.1: Experimental setup for front finger pad analysis. The robotic platform (left) is used to move the transparent plate of glass in contact with the finger pad. Two light sources light the finger from the front while a camera films the finger. A light under the plate lights the finger from the bottom, through the moving glass plate.

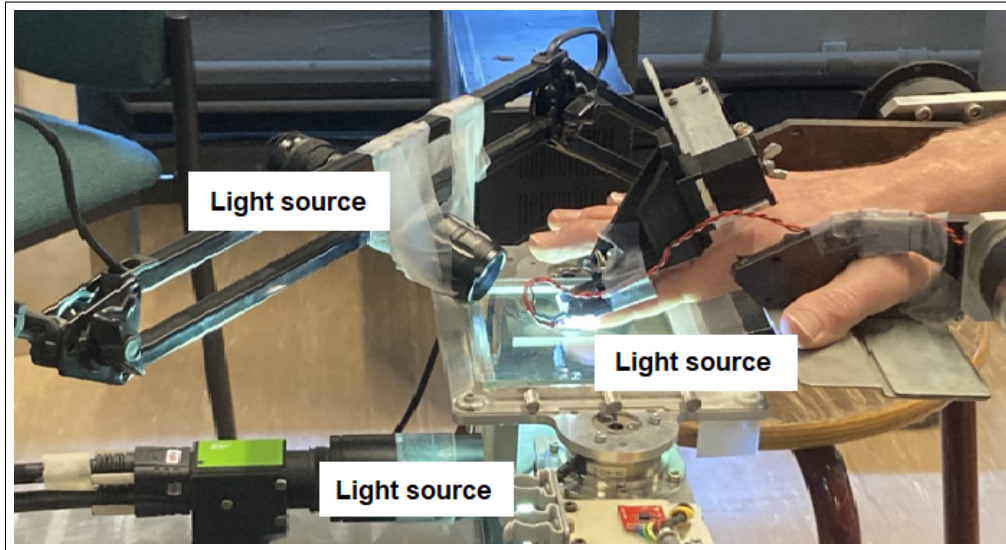


Figure 2.2: Second experimental setup view for front finger pad analysis. Three light sources are used : two from the top and one from the bottom, through the glass plate.

The imaging system includes a camera that is fixed on the ground and not linked to the moving robot. The camera acquires images of the fingertip from a front point of view as depicted in figure 2.3 (b). Those images are acquired at high frequency (100 frames per second) and high resolution (Allied-Vision Prosilica GE680, 640 x 480 pixels, 12 Bit ADC). We obtain the fingertip ridges at high contrast with a light exposition from different directions. Images are acquired thanks to a video acquisition board (NI PCIe-1433) mounted on a dedicated high-speed memory access computer. A TTL trigger is used to synchronize both acquisition boards. We calibrate the camera through the use of a reference frame that is painted on the index support and appears at the top of each frame.

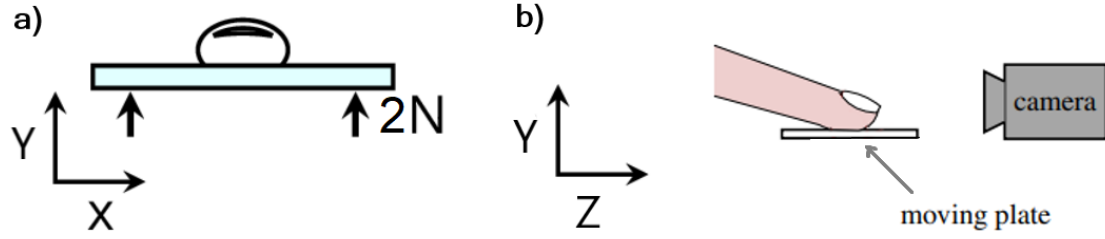


Figure 2.3: (a) The finger is pressed by its support with a servo-controlled normal force ($2N$ here). The plate moves tangentially in one of four directions (ulnar, distal, radial or proximal). (b) At the same time, a camera is used to image the front finger pad. The illustrated coordinate system is the standard system we use in this work. Figure from [9]

Finally, in order to collect data about the lateral displacement and strain fields, we set up a new configuration. Here, we displace the camera next to the finger, as illustrated in figure 2.4. Since the setup is tinkered, recorded frames are to be processed accordingly (rotation).

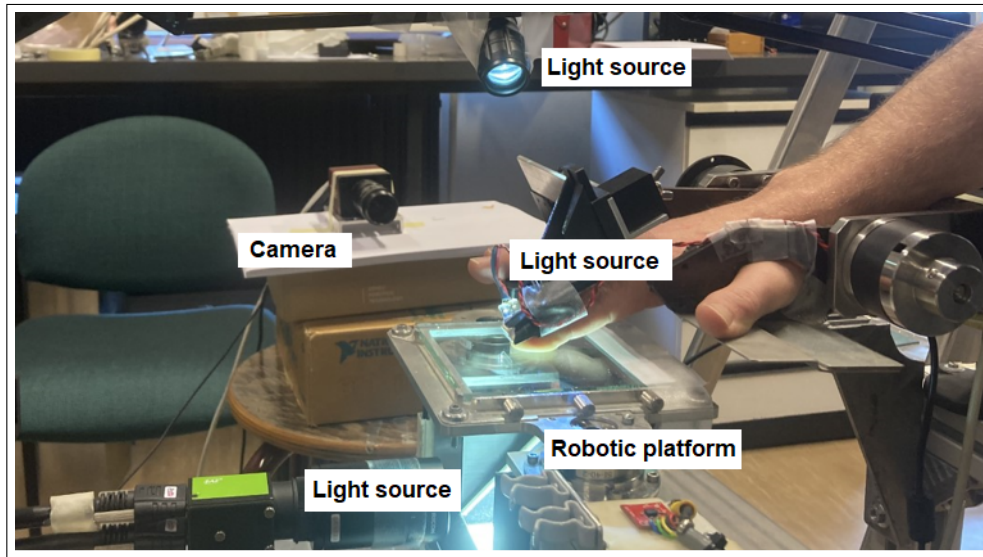


Figure 2.4: Experimental setup for lateral finger pad analysis. The camera is displaced next to the finger. Lights are kept but they are reoriented to optimize the lighting.

2.1.2 Experimental protocol

Three healthy volunteers participated in the experience. They were asked to rest their index on the support and to relax. The protocol is as follows : the robotic plate translates in four perpendicular directions : ulnar, radial, distal and proximal. The transparent plate moves at 5 mm/s. The setup applies 3 different normal forces on the finger : 1,2 and 5 N. The plate moves in a two-dimensional plane. That is, there is no vertical movement in the y direction (see figure 2.3 to know more about the used coordinate system). We repeated the process 5 times for each situation. We recorded 180 videos for the front analysis. Regarding the lateral analysis, we ran the same protocol but with two volunteers. We recorded 120 videos. In total, for this master thesis, we recorded 300 videos.

2.2 Data Analysis

2.2.1 Force and position data

Force data were low-pass filtered with a fourth-order digital Butterworth filter with a cut-off frequency of 80 Hz and zero phase lag. The image acquisition rate is 100 frames per second. Speed data was deduced from position data.

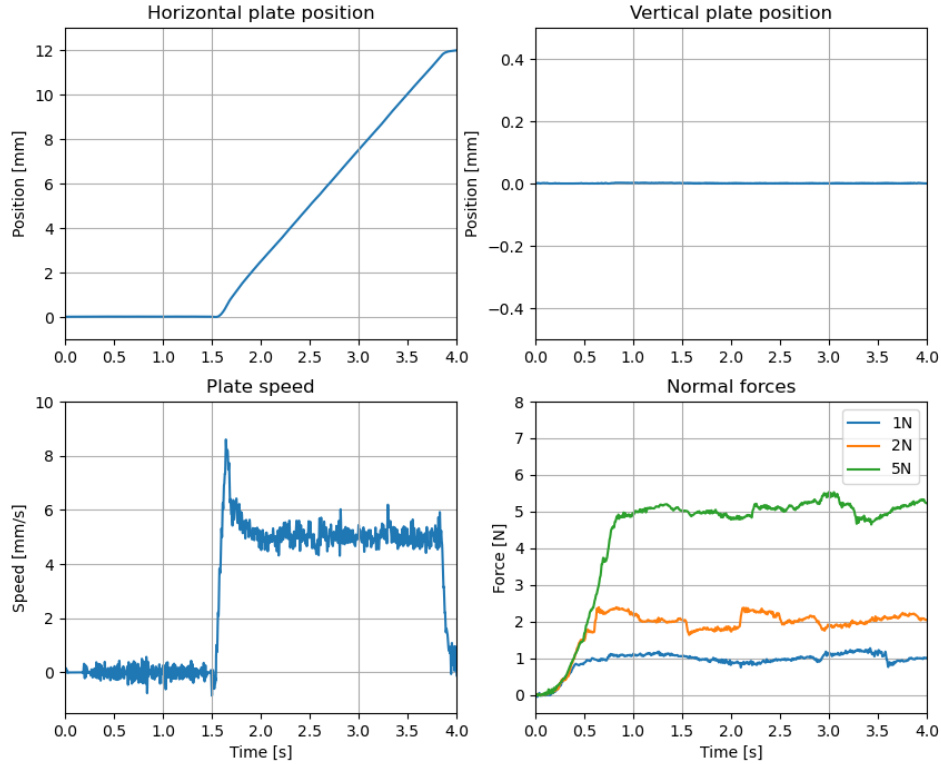


Figure 2.5: Position and speed profiles during one example trial. Force profiles are extracted from three different trials (subject S01).

Figure 2.5 shows force, position and speed profiles during one example trial. Horizontal plate position is the plate displacement in the stimulus direction. Vertical position is the plate displacement according to the y axis. This latter is null : the plate only moves in a two-dimensional plane. The finger is loaded after 1 [s], the plates moves after 1.5 [s] and finally the fingertip fully slips after 3 [s], according to our observations.

2.2.2 Displacement field

The displacement field is obtained thanks to a computer vision method based upon the Lucas-Kanade method, called optical flow. This method tracks points that follow the fingertip features and thus its deformation. We've developed a Python routine based upon a popular library in computer vision, openCV [5]. The method follows the next procedure.

First, we sample a large number of features of the fingertip on the first frame. Those features are chosen according to tracking performance criteria [18] and thanks to a function available in openCV: `goodFeaturesToTrack()`. Distributed trackers are more or less equally spaced : 26 pixels. The total amount of trackers ranges from 45 to 60. The reason why the number of trackers varies is that, for proximal and distal movements, some trackers are occluded before the last frame. Hence, we decide to discard them. The other reason is that for upper force levels such as 2 and 5N, the visible finger area where trackers are distributed gets smaller. Anyway, we run the optical flow method to track trackers frame by frame until the end of the video. The Lucas-Kanade method makes the assumption that changes between two frames are small and that the flow is almost constant in local neighbourhoods, centred around trackers of interest. From this, the algorithm computes the basic optical flow equations for all the pixels within that neighbourhood (also called the window), by the least-squares criterion [14]. In those conditions, it is obvious that lighting has a critical influence on tracking performance. Finally, we record the position of each tracker for each frame in a Python array to obtain our displacement field. It is ready to be handled by a strain analysis algorithm, already developed and used in previous studies [7, 9]. The strain derivation method is explained in the next section.

2.2.3 Strain derivation

We use a strain derivation method detailed in the paper that has been previously developed [7, 9]. For more clarity, we rewrite it down here. We seek to compute axial Green-Lagrange strains by displacement gradient, from the displacement field mentioned above. We estimate strains thanks to equations (2.1a) and (2.1b)

$$\epsilon_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right] \quad (2.1a)$$

$$\epsilon_{yy} = \frac{\partial v}{\partial y} + \frac{1}{2} \left[\left(\frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right] \quad (2.1b)$$

In those equations, ϵ_{xx} and ϵ_{yy} are the *axial strains* along the x and y axis respectively. u and v are the *displacements*, once again along the x and y axis respectively. A Delaunay triangulation is constructed on the trackers (or the feature points) from the first frame. For each triangle.. Each triangle has vertices coordinates (x_1, y_1) , (x_2, y_2) , (x_3, y_3) and displacement fields at these coordinates (u_1, v_1) , (u_2, v_2) , (u_3, v_3) . The triangle displacement field is computed and attributed to its centre (see figure 2.6).

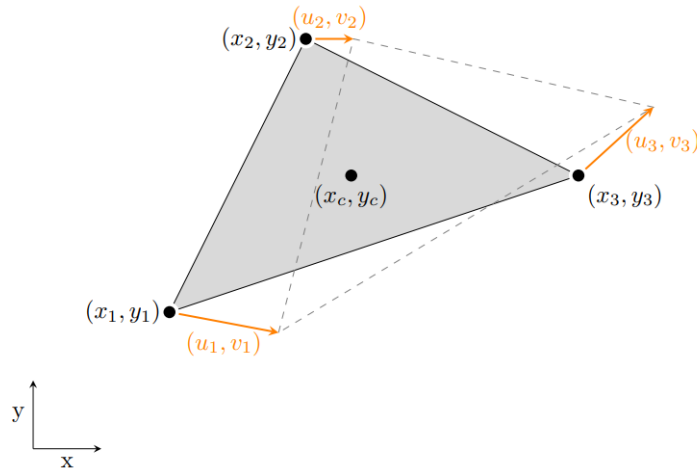


Figure 2.6: Elementary triangle from the Delaunay triangulation. Figure from [7].

2.2.4 Tracking evaluation

In the section displacement field, we said we build the displacement field thanks to a tracking algorithm named optical flow. Although this algorithm is reputed to be efficient, tracking performance depend a lot on the environment and the feature or data that is being used for tracking purpose [17]. We can measure the ability of an algorithm to track features thanks to tracking metrics. In this section, we will present two metrics to evaluate the tracking performances of our methods.

The objective of a tracking algorithm is to correctly update trackers position on their assigned features. The first metric we use is the Object Tracking Error (OTE) [17], depicted in equation 2.2.

$$OTE = \frac{1}{N} \sum_i^N \sqrt{(X_{gi} - X_{ri})^2 + (Y_{gi} - Y_{ri})^2} \quad (2.2)$$

In the equation 2.2, X_{gi} and Y_{gi} are the ground truth coordinates of the features on the last frame while X_{ri} and Y_{ri} are the actual trackers coordinates on the last frame. N is the amount of used trackers. The OTE measures the average euclidean distance between both. Although this method seems complete, it has a drawback: it doesn't take into account the displacement. Indeed, a 5 pixels error is much more annoying on a 10 pixels displacement than on a 20 pixels displacement. Therefore, we must use a second metric, in addition to this one, that we call Weighted Object Tracking Error WOTE, depicted in equation 2.3. With this new metric, we normalize the error with the distance travelled by the trackers between the first and the last frame. To avoid errors to artificially explode for trackers with a small displacement, we discard trackers that have a displacement norm below 10 pixels. In this equation, $\sqrt{X_{di}^2 + Y_{di}^2}$ is the distance in pixels travelled by the i^{th} tracker.

$$WOTE = \frac{1}{N} \sum_i^N \frac{\sqrt{(X_{gi} - X_{ri})^2 + (Y_{gi} - Y_{ri})^2}}{\sqrt{X_{di}^2 + Y_{di}^2}} \quad (2.3)$$

Ground truth coordinates have manually been obtained, by inspecting the features positions on videos from the first to the last frame. Note that if equations 2.2 and 2.3 measure averages, we will rather measure the error distribution with box-plots.

2.2.5 Spatial influence

If we run the tracking algorithm and consider only trackers that were present on the first frame until the last frame of a video recording, we obtain the results illustrated in the figure 2.7. This figure shows the tracking at four different times for the first subject S01 at 1N force loading. The first obvious result is the difference in performance between the trackers laid on the border and the trackers distributed in the finger pad bulk. Whereas trackers located in the bulk seem to be able to follow their assigned features in deformation, trackers located on the border slide along this latter. That is, they are able to track the border but not the specific points on the border they were assigned to. Therefore, we decide to keep trackers in the bulk as they are and to discard trackers on the border. To track the border deformation, we use another method. We use the openCV function `threshold()` to extract the finger shape at each frame to sample points at its border. Then, we interpolate those points before to smooth the curve with a Savitzky–Golay filter. We describe the performance and the results of our methods in the next sections.

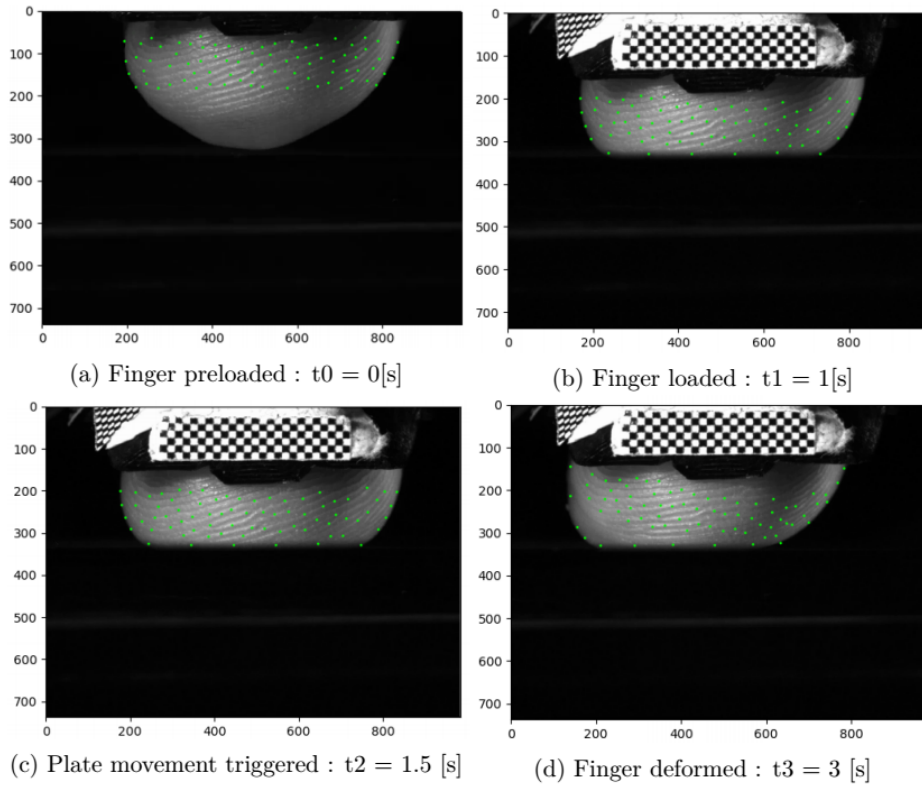


Figure 2.7: Front fingertip tracking : ulnar shearing example trial for subject S01 at 1N.

2.2.6 Border interpolation

We know from the previous section that trackers slide along the border without tracking particular points. Therefore, thanks to image processing methods like image binary thresholding and other computing tools, we managed to build the border envelop of the fingertip under shearing. Figure 2.8 shows the tracking performance at four different times for the first subject S01, at 1N force loading. Our objective is to measure the distance in contact with plate as well as the visible area comprise between the top plastic structure, or more simply the interpolated polygon area. From those frames, we notice that our algorithm manages to envelop quite well the fingertip. Similar results have been obtained with other subjects and other force levels (2 and 5N).

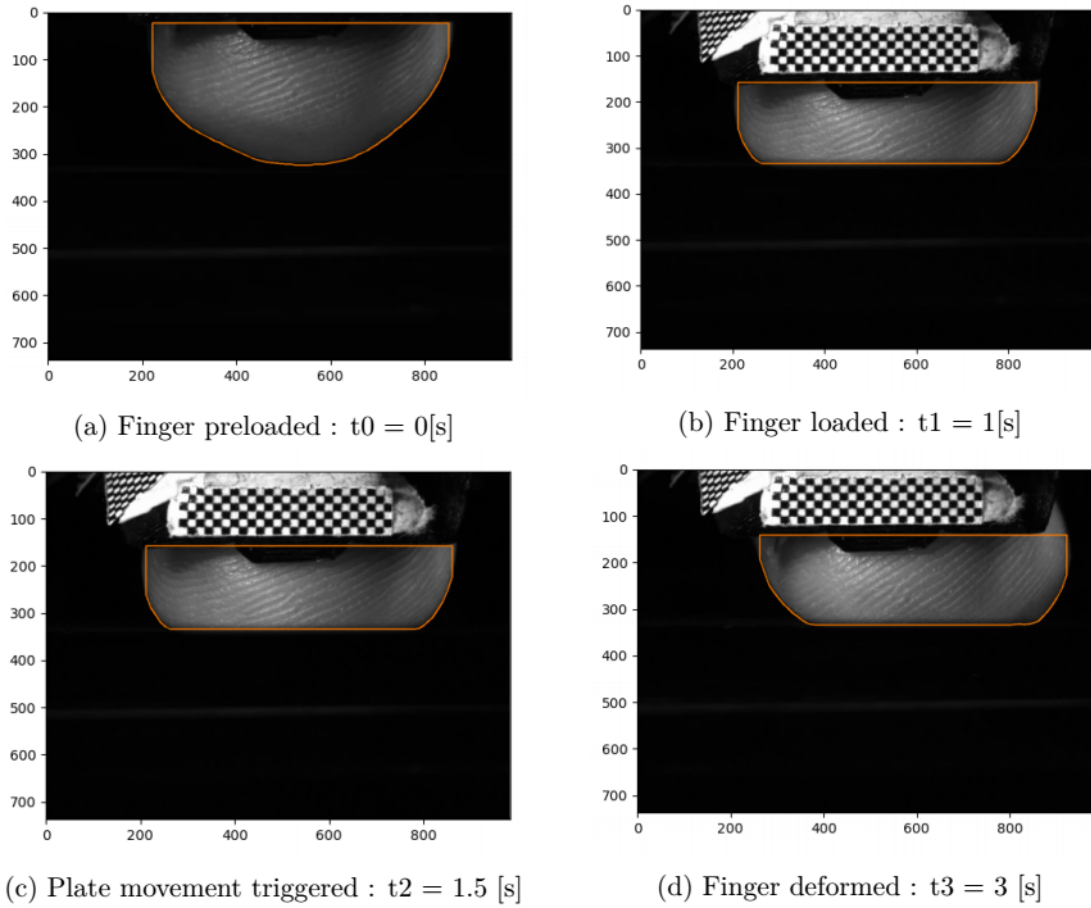


Figure 2.8: Experiment phases: radial shearing example trial for subject S01 at 1N.

2.2.7 Frame rate influence

Regarding the tracking validation for trackers in the bulk, we propose to quantify it according to the metrics introduced in the tracking evaluation section. We run the experiment in the four directions at 1N force level for the subject S01. We test the tracking algorithm for 55 trackers in average for each video. Thus, 220 trackers in average. Figure 2.9 shows the tracking performance. The first result that comes out is the influence of the temporal resolution. Besides loading movement, we observe very bad results when we execute the tracking on videos at 100 frames per second. After some investigation, we found out that the tracking gets better with a lower frame rate. We reach a peak of performance for 25 frames per second.

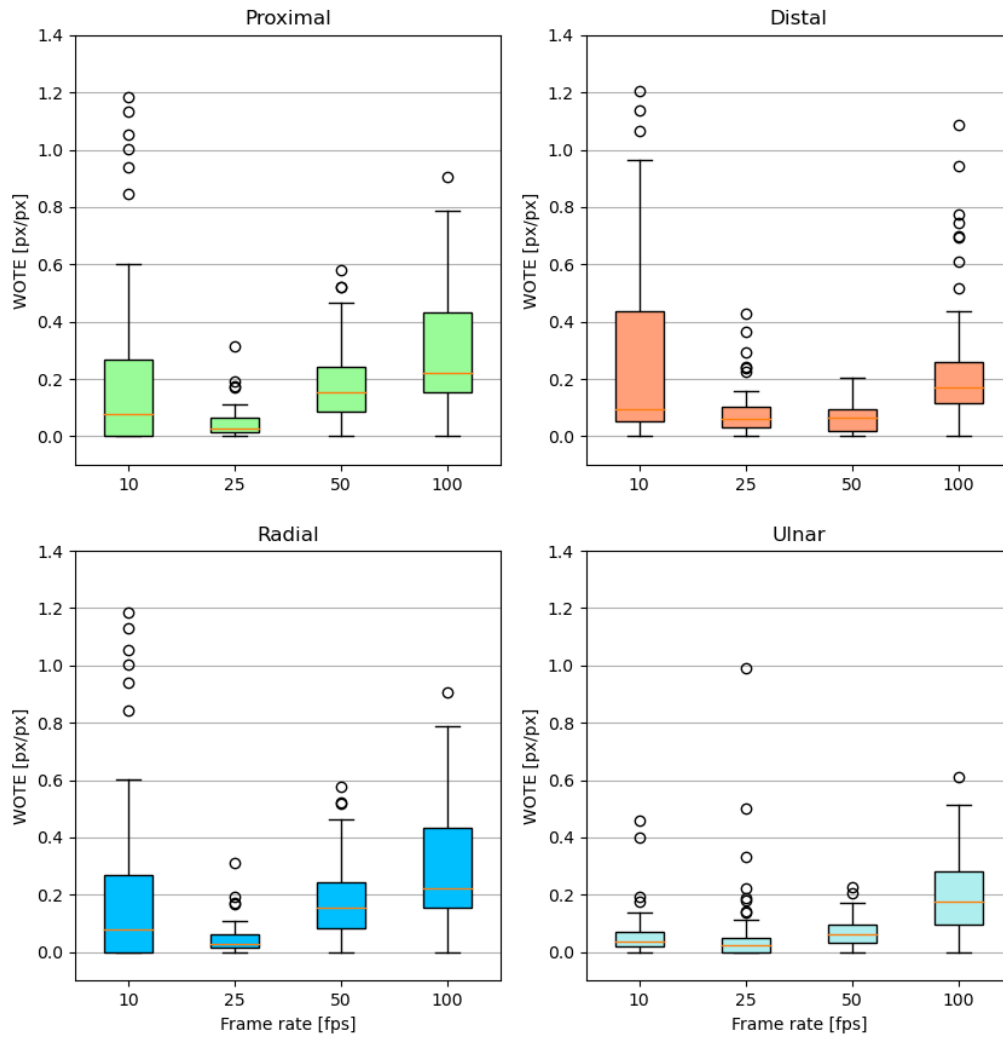


Figure 2.9: Tracking performance for front analysis based on the frame rate for subject S01 at 1N force level. The test has been made on 55 trackers in average. The orange horizontal line stands for the median.

Here, the error is the same that occurred when we attempted to track the border of the finger pad in the previous section : sliding. However, whereas trackers in the border slide along the limit of the finger, trackers in the bulk slide along the fingertip ridges. That is, they manage to track the ridges, but not specific points they were assigned to in the ridges. Figure 2.10 illustrates the importance of error in function of the spatial localisation. We observe that poor performance trackers are especially located in the sides of the bulk, where wrinkles deformation is very important, but also in locations where the light is less important, highlighting the need of a good lighting. Camera calibration is done thanks to the chessboard on the support above the bulk. The resolution is 36 [px/mm].

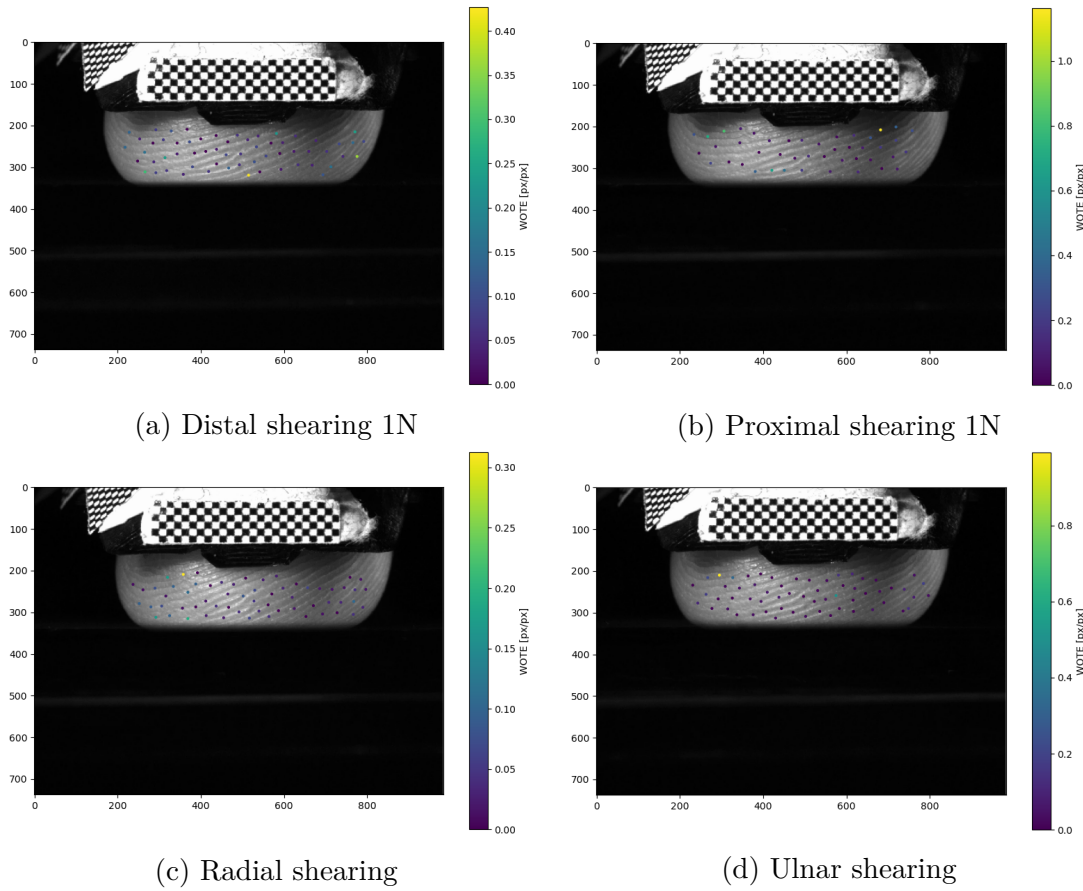


Figure 2.10: Front shearing : trackers performance distribution for subject S01 at 1N.

Figure 2.11 compares the performance difference between 100 fps and 25 fps for different movements, according to WOTE and OTE metrics. It is important to note that loading is not affected by the high frame rate. The figure shows it has a WOTE less than 5 %.

We don't really understand why we have such bad performance. We think it is due to the ridges deformations that change the tracked features. Trackers show indeed good performance during loading, until shearing. However, such results didn't happen in previous publications that study fingerprint deformations [7, 9]. Yet, ridges were strongly deformed too. But on the other hand, the resolution in those studies was higher : 52 [px/mm] and deformation took place on a plate, with a good focus throughout the studied area. In our case, although we've taken care to have an acceptable depth of field, tracking conditions are not as good: we image a complex three-dimensional object with a lower resolution. Another cause could have been the noise and variation of the lighting throughout a trial, but we band-filtered frames and it didn't solve the problem.

Hence, given that only the loading yields good tracking performance at 100 fps and since the fingertip is a complex 3D structure, we analyse strains exclusively for this move in the front side of the finger pad.

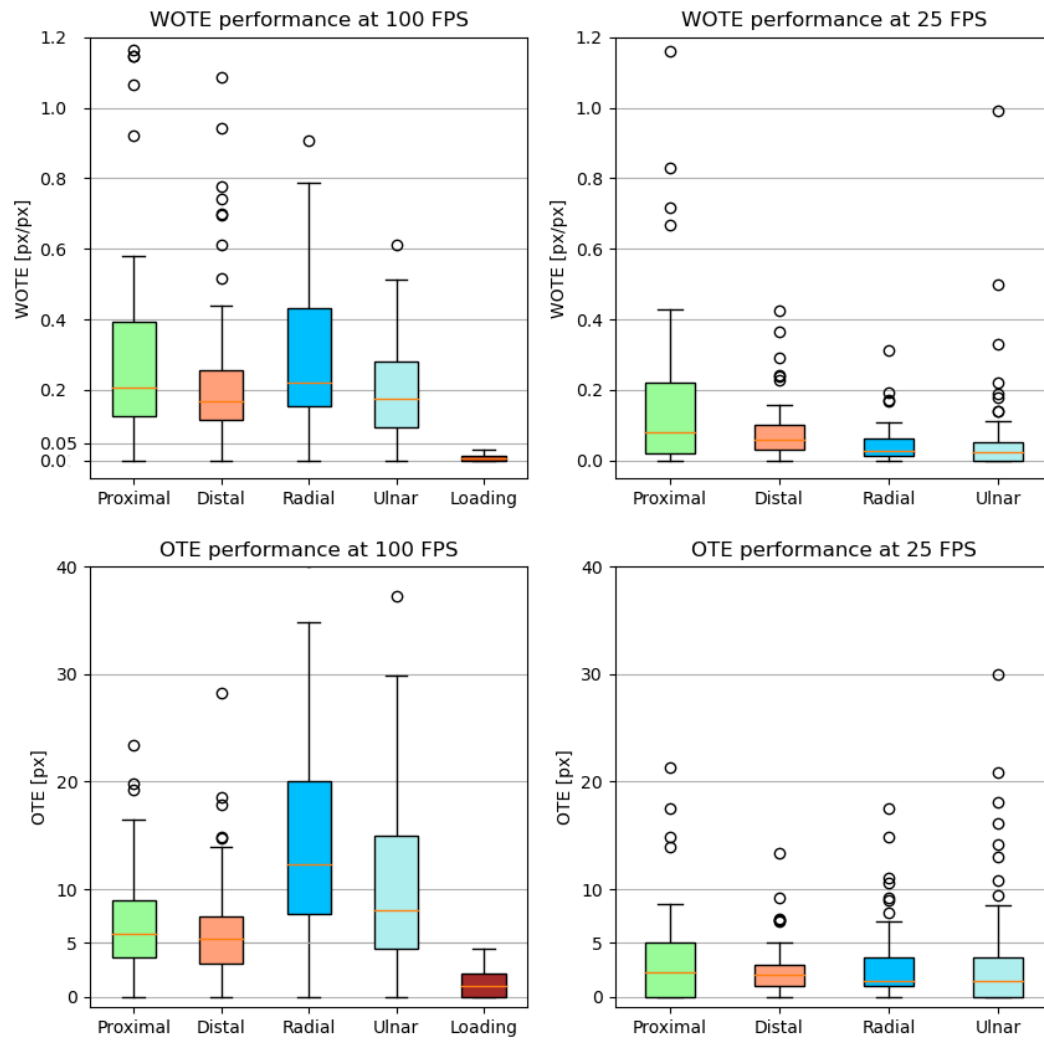


Figure 2.11: Tracking performance for front analysis based on movement and on frame rate. The test has been made at 1N force level on 55 trackers in average for subject S01.

2.2.8 Lateral analysis

In the last section, we said we won't analyse strains in the front side of the fingertip during shearing because of a lack of tracking performance and the complex structure of the front fingertip. However, it would be interesting to know, if tracking was efficient, what would be the error we would make by measuring strains in a 2D plane that approximates strains in a 3D structure. We would like to know how far trackers could go in the plane (according to the z axis) and if measuring strains with only one camera is relevant. More generally speaking, we want to study the displacement field in the lateral side of the fingertip. Moreover, the lateral side of the fingertip is less complex than the front since it's more 'flat'. Therefore, we can suppose more reliable measurements (we film the lateral part with a single camera too).

In this section, we present our method to track the features in the lateral part of the finger. Not much change: we apply the exact same procedure as before. We scatter trackers thanks to the openCV function *goodFeaturesToTrack()* and we launch the tracking algorithm based upon the Lucas-Kanade method (see data analysis - displacement field). Videos were extracted with the setup introduced in the data collection section, see figure 2.4

Tracking performance and its underlying limitations for lateral analysis is very similar to front analysis. On one hand, the frame rate has a great influence over performance for ulnar, radial, proximal and distal movements. On the other hand, loading tracking doesn't have this problem, just like the front tracking. Hence, we directly show performance at 25 fps for the 4 main movements and at 100 fps for the loading. Figure 2.12 shows the tracking performance in these conditions.

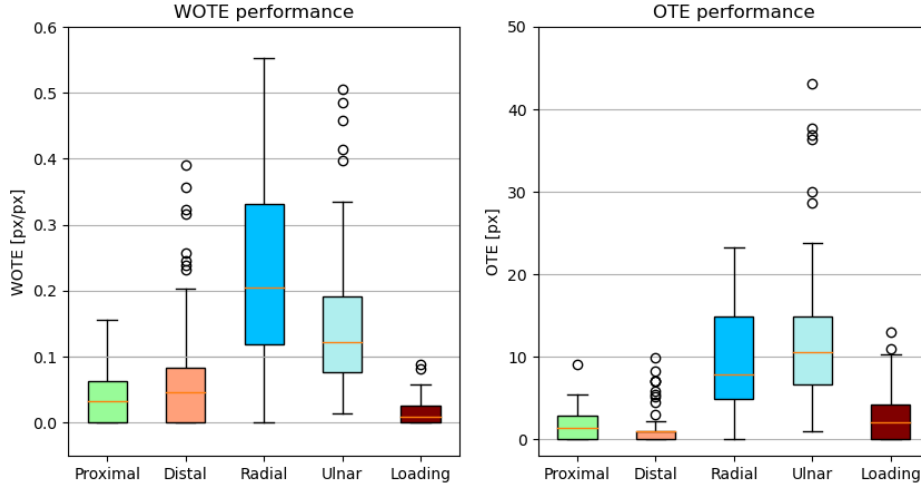


Figure 2.12: Tracking performance for lateral analysis. Proximal, distal, radial and ulnar movements are studied at 25 fps. Loading is studied at 100 fps. The test has been made at 1N force level on 55 trackers in average for subject S01.

If proximal and distal movements show good performance with an error median turning around 5%, ulnar and radial movements have a median error above 10%. The reason is that ridges deformation are such that they make the trackers to slide even more, despite of a lower frame rate. Those strong deformation also lead to strong light variation but this was solved with a high-pass filter. Figure 2.13 shows how trackers are distributed in the finger according to their performance. The resolution is 15 [px/mm]. Since we only keep trackers that have less than 10% error according to the WOTE metric, the main consequence is a low amount of used trackers for those movements: a bit less than 15 trackers in average will be kept for the lateral analysis for ulnar and radial shearing. This is unfortunately low but we believe it will be sufficient to give an insight about the displacement field for those movements.

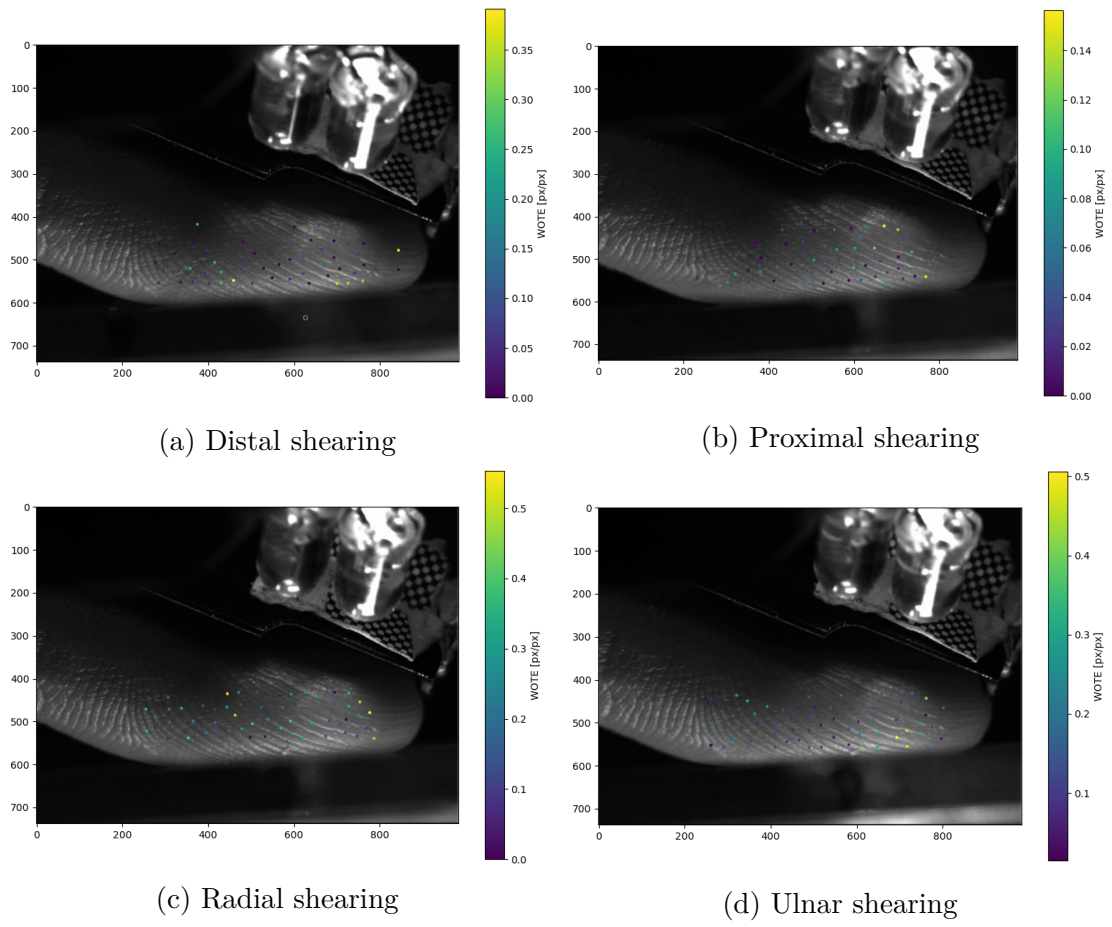


Figure 2.13: Lateral shearing : trackers performance distribution for a trial for subject S01 at 1N.

Chapter 3

Results

3.1 Border Tracking Evaluation

In this section, we present the finger length in contact with the plate and the visible area. Both are evaluated in time between 0 and 3.3 seconds. That is before loading and after full slip phases.

3.1.1 Evolution of the contact length

Figure 3.1 shows the contact length evolution of the subject S01. The four movements and the three forces are depicted. We can clearly observe the loading and how the finger rests on the plate. When the finger is loading, the contact length very quickly increases until the end of the phase. Then, a plateau persists during 1 second. Thereafter the contact length decreases with the plate movement after 1.5 second. Next, the finger is deformed under shearing: we observe variations in the contact length until the full slippage that happens after 3 seconds. The contact length finally stabilizes.

We also see that the contact length increases with the force. This was expected since the fingertip is more pressed against the plate when the normal force is higher. However, the increasing remains moderate, just a few mm.

Similar results have been obtained with the two other subjects. Scales may just change because the finger morphology changes from a subject to another. You can find these results in figures A.1 and A.2 in the appendix A.

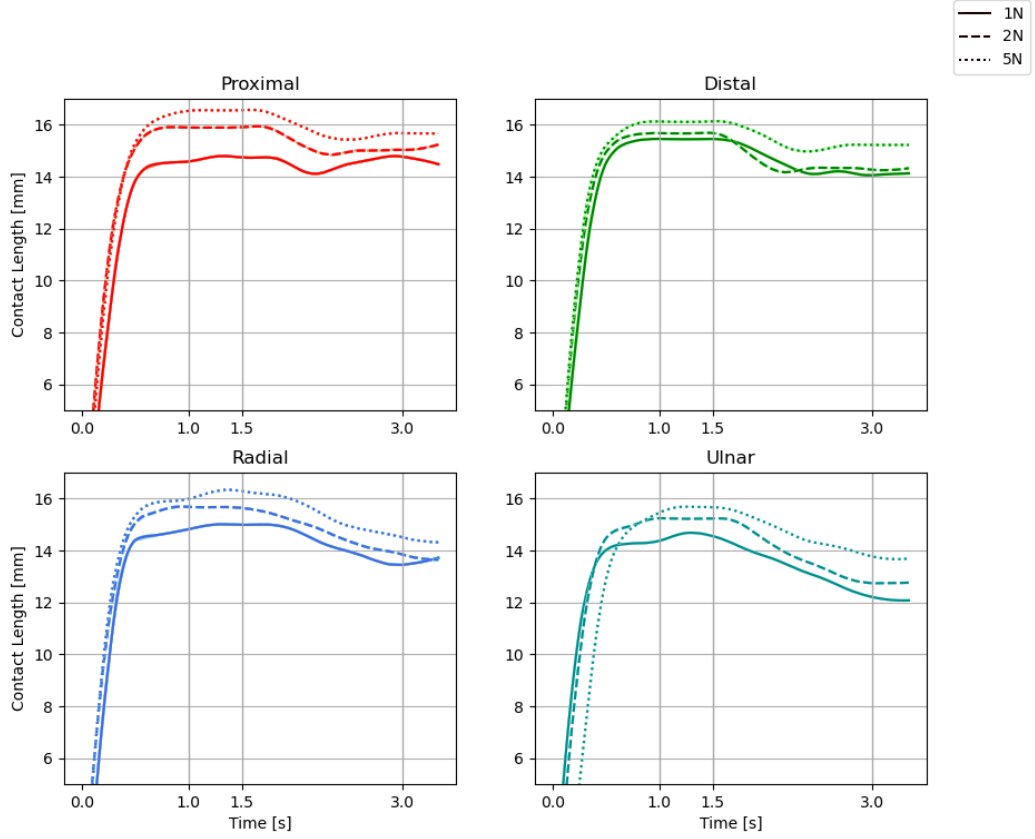


Figure 3.1: Contact length evolution for subject S01

3.1.2 Evolution of the visible area

The visible area corresponds to the area of the polygon that interpolates the shape of the finger, as illustrated in figure 2.8. Figure 3.2 shows the evolution of this area for the four movements, for the three forces for the subject S01. For each condition, the area starts to decrease with the loading. After 1 second, the bottom of the finger is occluded. The area increases when the plate start to moves for distal, ulnar and radial movements. This increasing is due to the fact that with the finger deformation, more flesh, previously hidden by the structure or by the front fingertip, appears. Yet, the proximal movement makes the exception : the visible area doesn't increase because the skin is pull backwards by the plate here. Thus, no flesh appears to the screen.

We also see that the area decreases with the normal force, which is normal since more flesh is occluded as the finger is more pressed against the plate. Similar results have been obtained with the two other subjects. The difference we can observe is that the difference in morphology and in elasticity makes that for some subject, less flesh appears at the loading or during the plate movement. As a matter of fact, the subject S02 looks to have a stiffer skin, hence less variability. You can find these results in figures B.1 and B.2 in the appendix B.

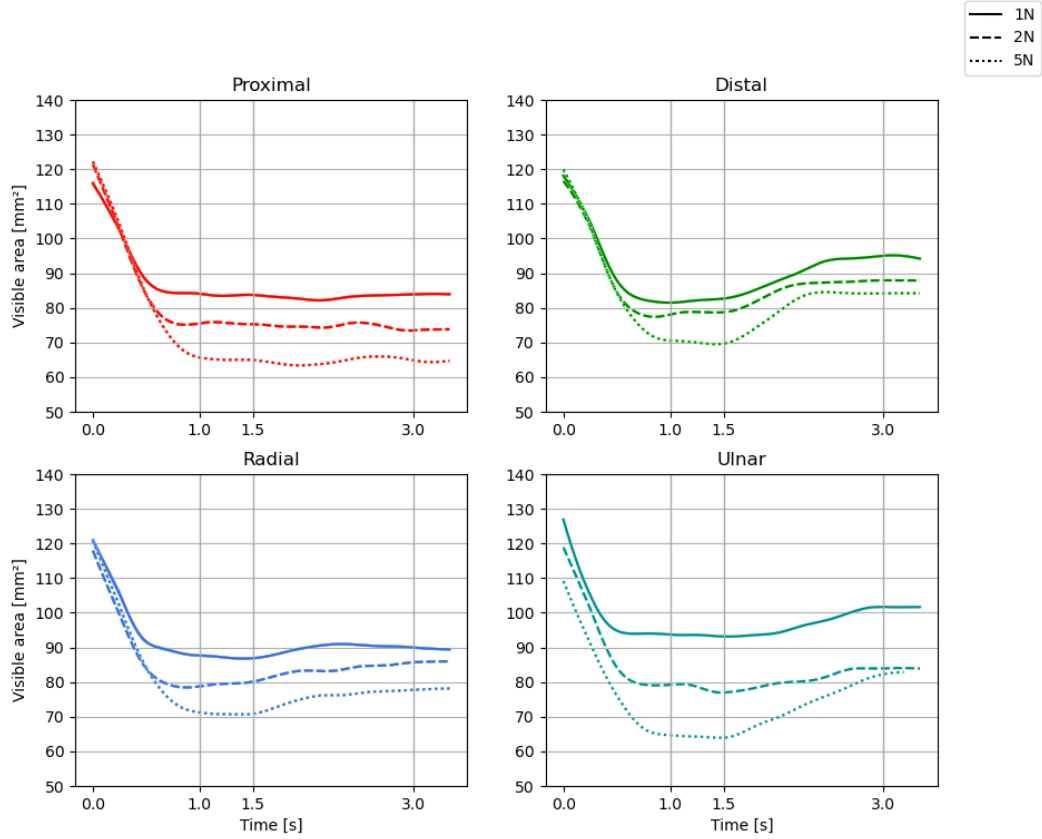


Figure 3.2: Visible area evolution for subject S01

3.2 Lateral Displacement Field

We are interested in the displacement field in the lateral side of the finger. Figure 3.3 shows the displacement field for the subject S01 at 1N normal force. The displacement field for the subject S02 is provided in the appendix C, figure C.1. Since we kept trackers with an acceptable error (less than 10 % according to the WOTE metrics), the amount of kept trackers varies from a movement to another as announced in the data analysis section. Data were collected over 5 trials for each condition. The frames have been rotated to align the plate with the horizontal axis.

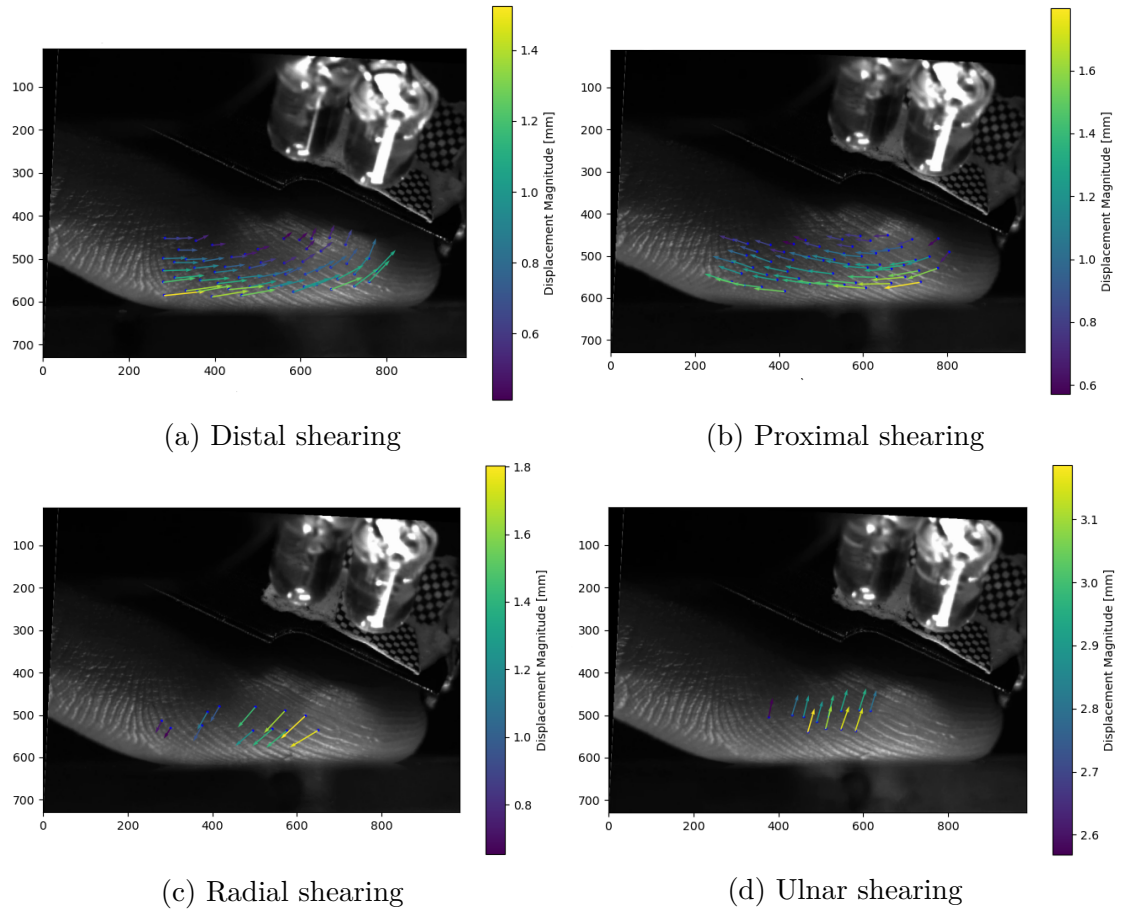


Figure 3.3: Lateral displacement fields : example trial for subject S01 at 1N

In a first time, we observe a displacement gradient. Distal and proximal movement yield a more intense displacement field near the plate. This is due to the fact that the bottom skin is urged to accompany the plate in its movement while the top skin is hold back by the top finger, fixed in the setup. We also see that the proximal movement has a larger amplitude than the distal. Indeed, the distal movement tends the already relaxed finger while the proximal compress it. Therefore, we have a larger displacement in this latter. Regarding the radial and the ulnar movement, we also notice a displacement gradient. But this time, we believe this is because of the geometry of the finger. That is, trackers look to travel a different distance, but they actually travel the same. Figure 3.4 shows a scheme of the pressed fingertip in the xy plane. The vertical displacement we measure are the distances ΔY_1 and ΔY_2 . Although ΔY_1 looks greater than ΔY_2 , the actual displacement is actually the same for both. We also see that ulnar shearing has a larger displacement. We explain this difference by a probable steeper curve at the bottom of the finger than at the top. The features go deeper in the plan in the bottom part. This is just a hypothesis, in the absence of perfect measurements of the finger shape to validate it. Since the shape of the finger varies from a person to another, we can expect different results with other subjects according to this hypothesis.

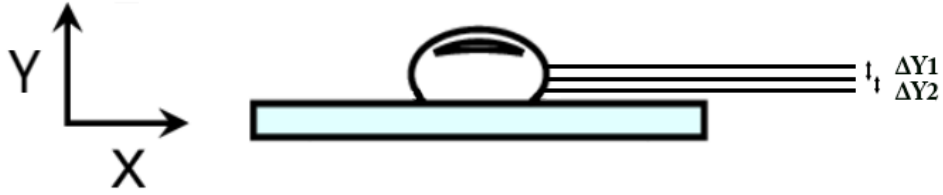


Figure 3.4: Finger pad front view

Finally, we observe that the displacement is two-dimensional. For the four movements, the displacement is not fully parallel with the plate move. Of course, the magnitude is always higher in the stimulus direction, but the displacement is not null in the respective perpendicular direction. There is a vertical displacement for the proximal and distal movement and a horizontal displacement for the ulnar and radial movement.

Figure 3.5 provides the quantified horizontal displacement amplitudes for different force levels and movements for the subject S01. Pay just attention that frames are defined such as the origin is at the upper left. Therefore, negative values, for vertical displacements, correspond to upward movements and vice-versa.

That said, let's take a closer look to it. We first see that for the subject S01 proximal and distal horizontal movement amplitude don't depend with the normal force. We can deduce that the subject S01 skin sticks to the plate, even at low force levels. Displacement is also greater in the proximal move but this was already discussed in the above paragraph.

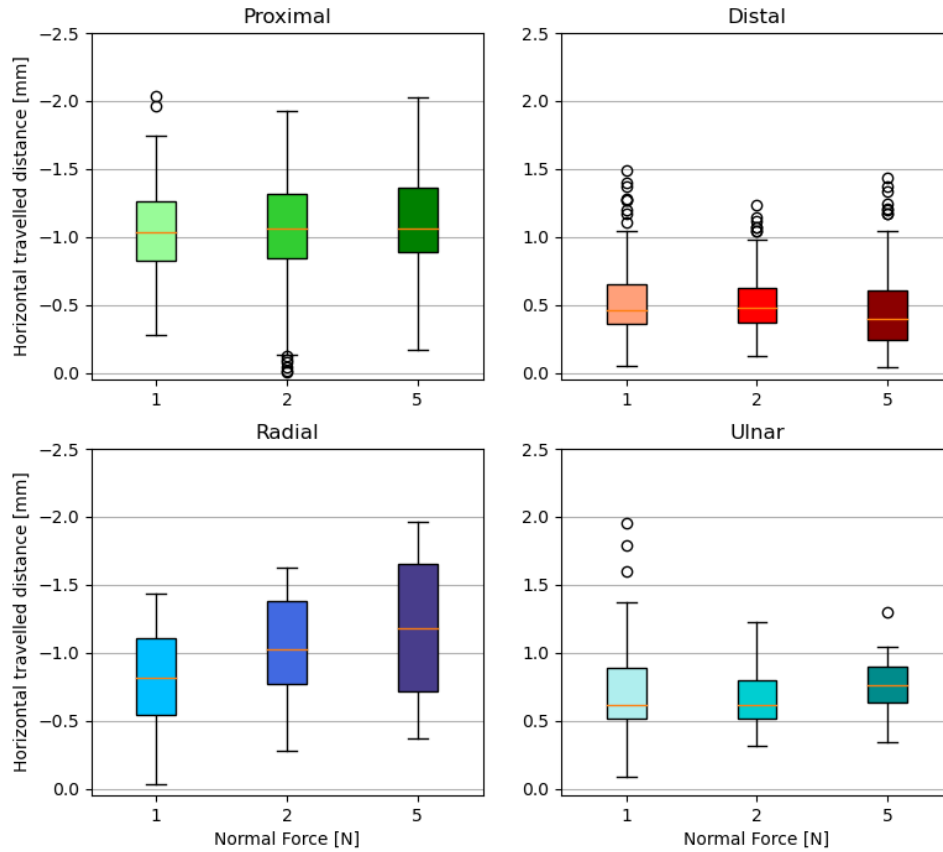


Figure 3.5: Horizontal displacement for subject S01

If you take a look to the horizontal displacement magnitude for the subject S02 in the appendix (figure C.3), you'll find light different results. First, we work at a lower scale: displacement magnitudes are not as large as with the subject S01. Then, proximal and distal amplitude movement looks to depend this time on the force. The ulnar movement seem to decrease with the force this time, but the change is on the order of 0.2 [mm], that is 3 pixels, which seems negligible when we know that trackers can vibrate within a 2 pixels radius. The difference between both subjects may be explained by the difference in skin flexibility and finger morphology.

Regarding the vertical movement, figure 3.6 shows the horizontal displacement for the subject S01. Proximal and distal direction don't show a significant dependence with the force too. If the ulnar movement seems to be independent of the force, we see an proportional relation for the radial. We believe that maybe, with a greater force, the finger of this subject flattens more and the vertical distance travelled looks greater because the curve gets steeper. Once again, in the absence of accurate anatomic measurement, this is just speculation.

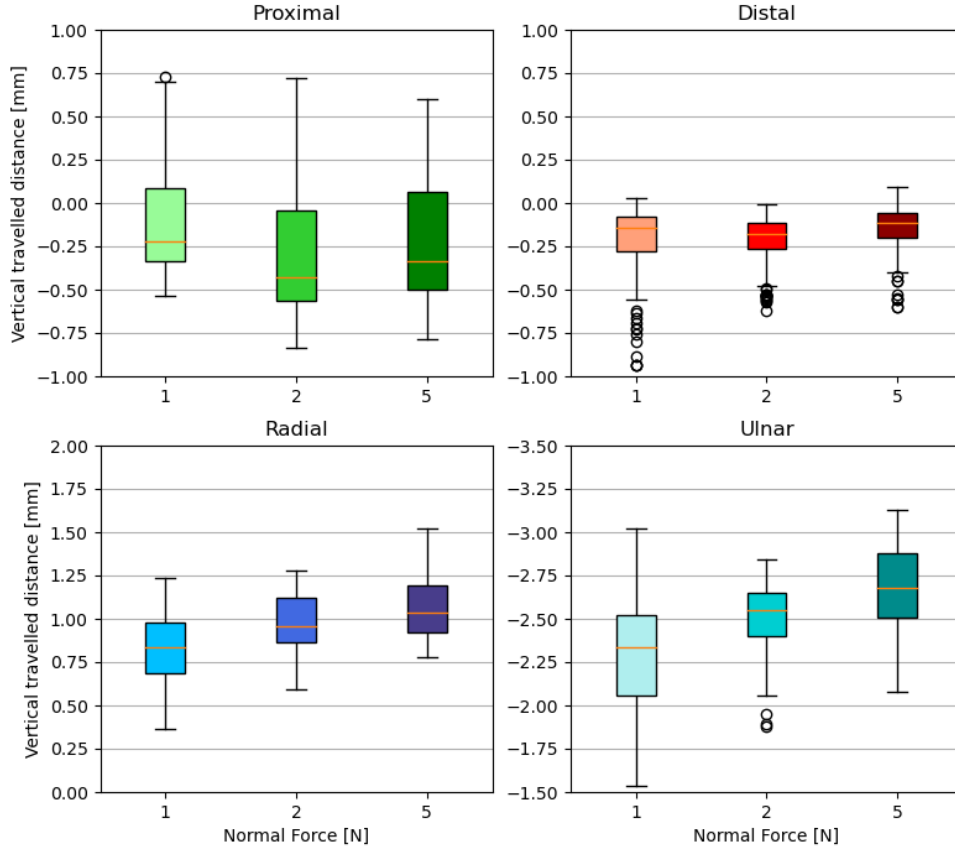


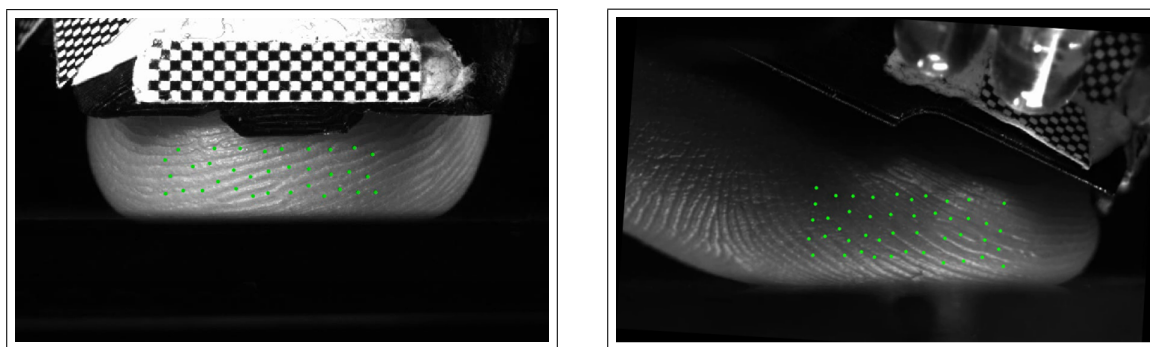
Figure 3.6: Vertical displacement for subject S01

If we compare with the subject S02 (figure C.3 from the annex), we notice that we work again at a lower scale. We also observe this time a slight dependence with the force for the distal shearing and a less important dependence for the ulnar.

In conclusion, we realise that we may have different results based on the subject. Finger geometry but also skin flexibility can vary a lot from a person to another. Moreover, we notice that ulnar and radial shearing generally has a greater displacement than proximal and distal and that they don't significantly depend on the force level. If we observe this difference, it's certainly because of the ridges that are more deformable in the transversal direction than in the longitudinal. Finally, the horizontal displacement can easily reach 1 [mm] amplitude and in some cases 2 [mm]. This has to be taken into account if we assume two-dimensional strains in the front part of the fingertip.

3.3 Strain Tracking Evaluation

In the data analysis section, we showed that the tracking has very poor performance at 100 fps, except for the loading. Moreover, because of the movements of the skin in depth (according to the z axis) described in the last section, it looks complicated to obtain relevant strains by a simple two-dimensional analysis. Therefore, we focus exclusively on the finger strains that appear during the loading. Figure 3.7 shows the tracker distribution for a typical trial.



(a) Front loading

(b) Lateral loading

Figure 3.7: Tracker distribution for a trial example (Subject 01 at 1N)

3.3.1 Frontal strain

We analyse the strains appearing in the front finger bulk for 300 videos and we observe that almost all the time, the strain field in the bulk is a relaxation field. Figure 3.8 is a trial that shows a typical example of this field with a typical strain amplitude. It represents the strain integration after the loading and before the plate start to move. Figure 3.9 shows how the field intensity varies from a subject to another and how it increases with the normal force. That is, higher is the force loading, higher is the relaxation.

This result might sound strange since we could have expected a compression field since the finger is pressed against the plate. However, it makes sense. Indeed, it's not the fingertip that is pressed, but the fingerprint. Hence, by conservation of the volume, since the fingerprint is pressed, the fingertip should inflate. This inflation increases with the force loading. This sounds logical since more pressure on the fingerprint means more inflation in the fingertip. Figure 3.8 shows that relaxation looks to be more intense in some parts of the bulk but, this distribution can vary from a trial to another, from a subject to another. We believe it can be

due to the tracker distribution that slightly varies at each video, or to the fact that the finger is not always loaded the same way with the same force everywhere or to the finger geometry that makes that relaxation can be more intense in a specific part of the finger. Finally, the field is not equally isotropic: horizontal relaxation ϵ_{xx} is higher than the vertical ϵ_{yy} . But, we must pay attention that we assume strains take place in a two-dimensional place here and that the finger is not an isotropic structure. Therefore, we should be careful with that measurement.

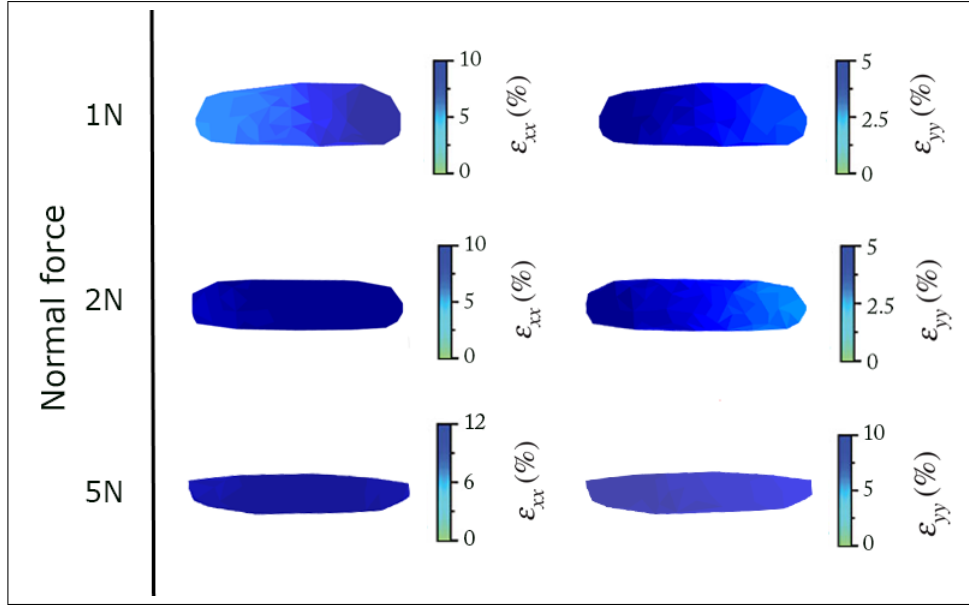


Figure 3.8: Strain field in the front finger pad for subject S01 at 1N force loading (after 1.3 [s]). The left field represents the horizontal strains ϵ_{xx} and the right field, the vertical strains ϵ_{yy} . The field was computed from the trackers displacement in figure 3.7a.

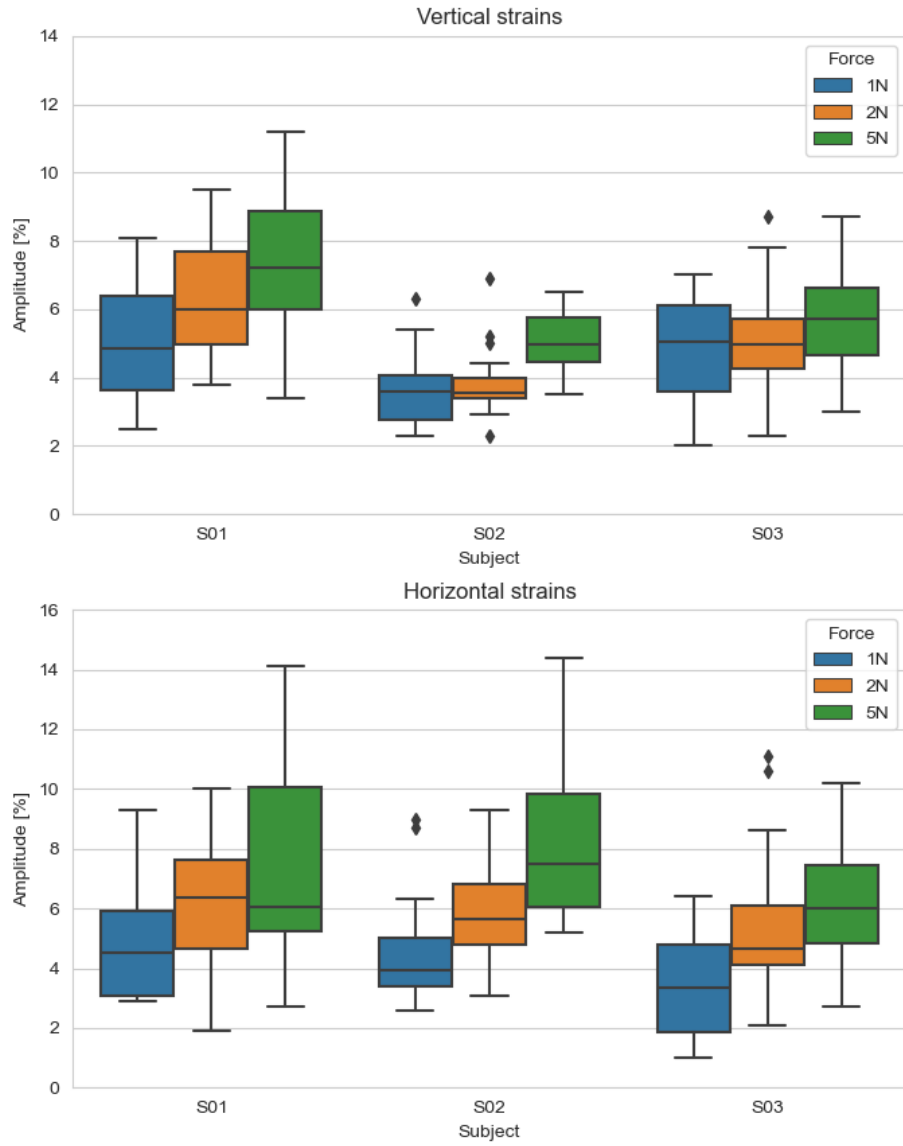


Figure 3.9: Front strain field intensity for three subjects for three loading forces

3.3.2 Lateral strain

We also analyse the strain field in the lateral part of the finger. This time, we have two subjects instead of three. As illustrated in figure 3.10, we observe similar results than with the front strain field : a relaxation field whose the intensity increases with the force. Once again, we deduce this is the inflation that results from the fingerprint compression. Figure 3.11 shows how the relaxing amplitude field is distributed among trials for different subject and force loadings. Once again, relaxation intensity depends on the subject and tends to get more intense with higher charges. The relaxation is also greater for horizontal deformation than for vertical.

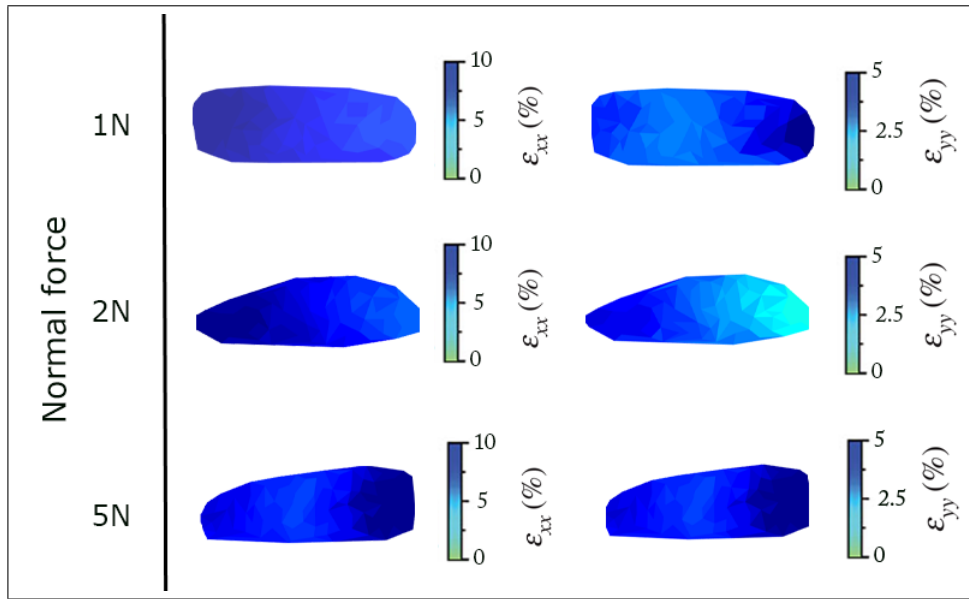


Figure 3.10: Strain field in the lateral finger pad for subject S01 at 1N force loading (after 1.3 [s]). The left field represents the horizontal strains ϵ_{xx} and the right field, the vertical strains ϵ_{yy} . The field was computed from the trackers displacement in figure 3.7b.

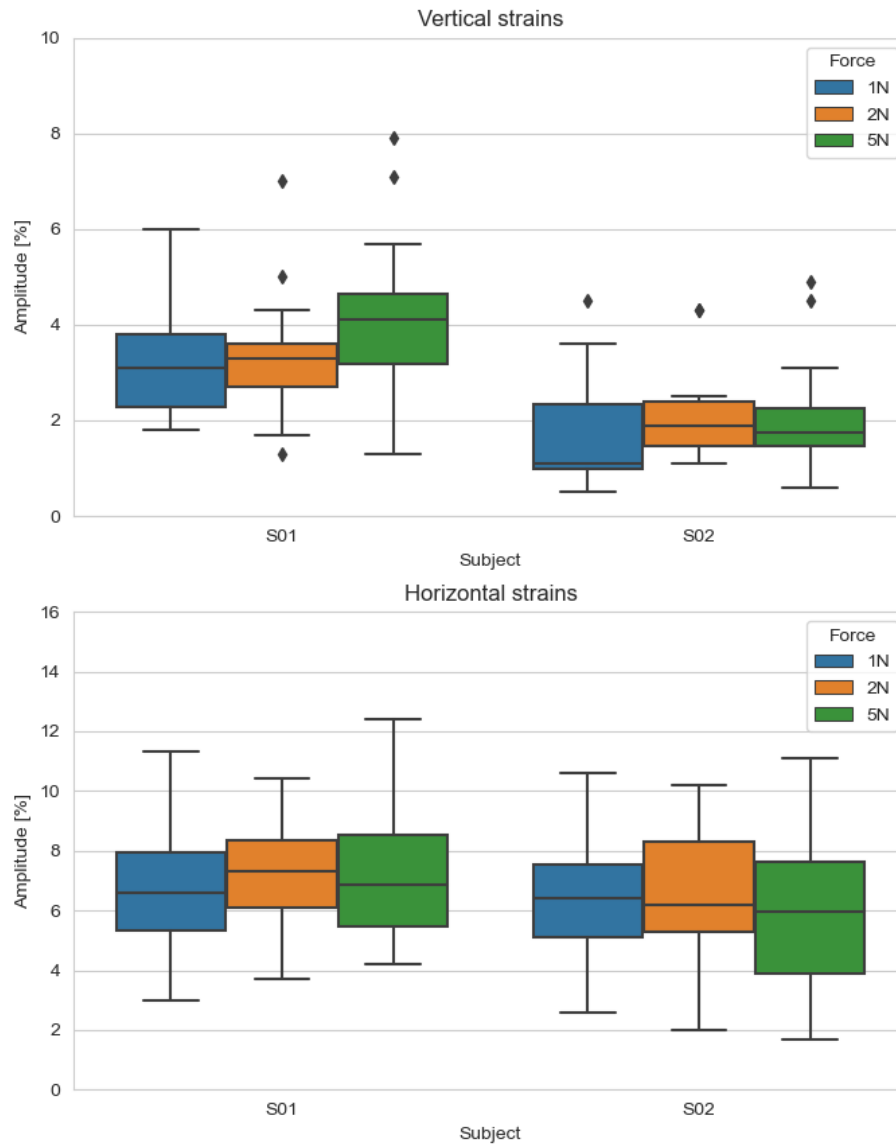


Figure 3.11: Lateral strain field intensity for two subjects for three loading forces

Chapter 4

Discussion

In this paper, we presented methods to collect data about how the lateral and the front part of the finger pad is deformed under loading and shearing. We measured the contact length with the moving plate and the visible area evolution when we observe the finger pad from a front point of view. We then studied the displacement field in the lateral part. Finally, we studied the strain field of the finger pad when it's loading.

This work shows that it is possible to track quite efficiently the fingertip border deformation as well as its visible area. Contact length and visible area data can be used to help to validate finite element simulations. However, it remains a two-dimensional analysis of a three-dimensional complex structure. Measures show that the contact length and the visible area depend on the subject. This was expectable since morphology can greatly depends from a subject to another.

This work also shows that features within the front fingertip bulk can be efficiently tracked at 100fps during loading but, that tracking finger shearing requires to use a lower frame rate. A better lighting could improve performance, but since band-filtering didn't solve the problem, I personally believe it is due to the wrinkle orientation change. Indeed, we don't have sliding with wrinkles that keep the same orientation and we don't have this problem for the loading, where wrinkles don't bend and shear in multiple directions. Hence, unless we draw markers with a pen on the fingertip, or greatly improve the resolution and the lighting, we don't have any choice so far to reduce the frame rate to have acceptable performance.

Tracking features in the lateral side of the finger to extract displacement fields shows great limitations for ulnar and radial shearing. However, Although, we only have less than 15 valid trackers for each video, it showed that the displacement field is not always parallel with the stimulus direction. We also observed that horizontal

movements (according to the z axis) can reach 2 [mm]. Therefore, when doing front strain analysis with a single camera, one must keep in mind that the 2D plane on which one distributes the trackers may slide in depth within a 2 [mm] range. Given that the finger is a convex structure, we can expect to have overrated strains near the border.

Finally, the strain analysis of the loading shows that the fingertip is not compressed as we could have expected, but relaxed. We explained this relaxation by the volume conservation that makes the fingertip to swell when the fingerprint is compressed. The flesh that is pressed in the fingerprint pushes the rest of the flesh in the fingertip in all directions, hence the relaxation field. We showed that the intensity of this field depends on subjects and is directly proportional to the loading force. Measures showed that the field is not equally isotropic : horizontal axial strains are more important than vertical. However, we said that, since we assume 2D strains in a 3D structure, we should be careful with this difference.

4.1 Perspectives

The current results are limited by the use of a single camera. A good knowledge of the finger anatomy, provided by a 3D reconstruction could yield more accurate results with less uncertainty. Moreover, since the lighting and lateral imaging setup was tinkered, a more accurate setup could lead to better tracking performance. With much more trackers distributed throughout the skin, we can hope to have more precise results. Drawing the fingertip with markers such as paint could be a good idea to boost tracking performance and thus provide a more comprehensive analysis.

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Appendix A

Contact length

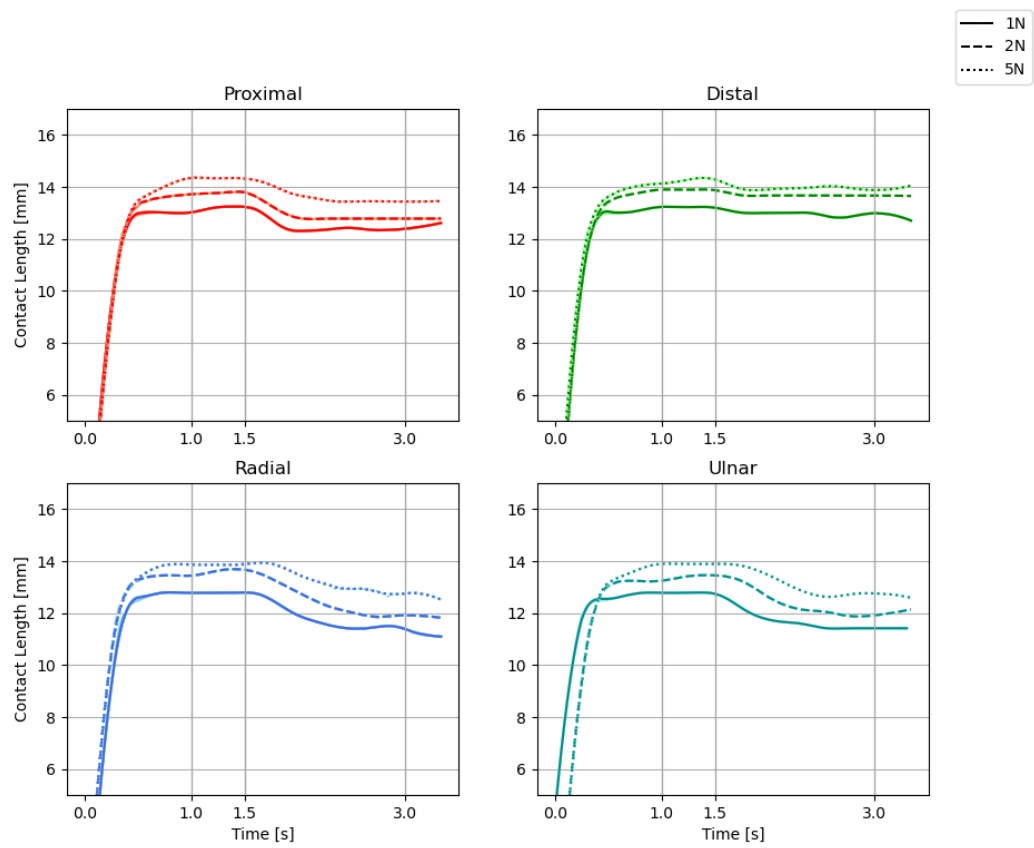


Figure A.1: Contact length for subject S02

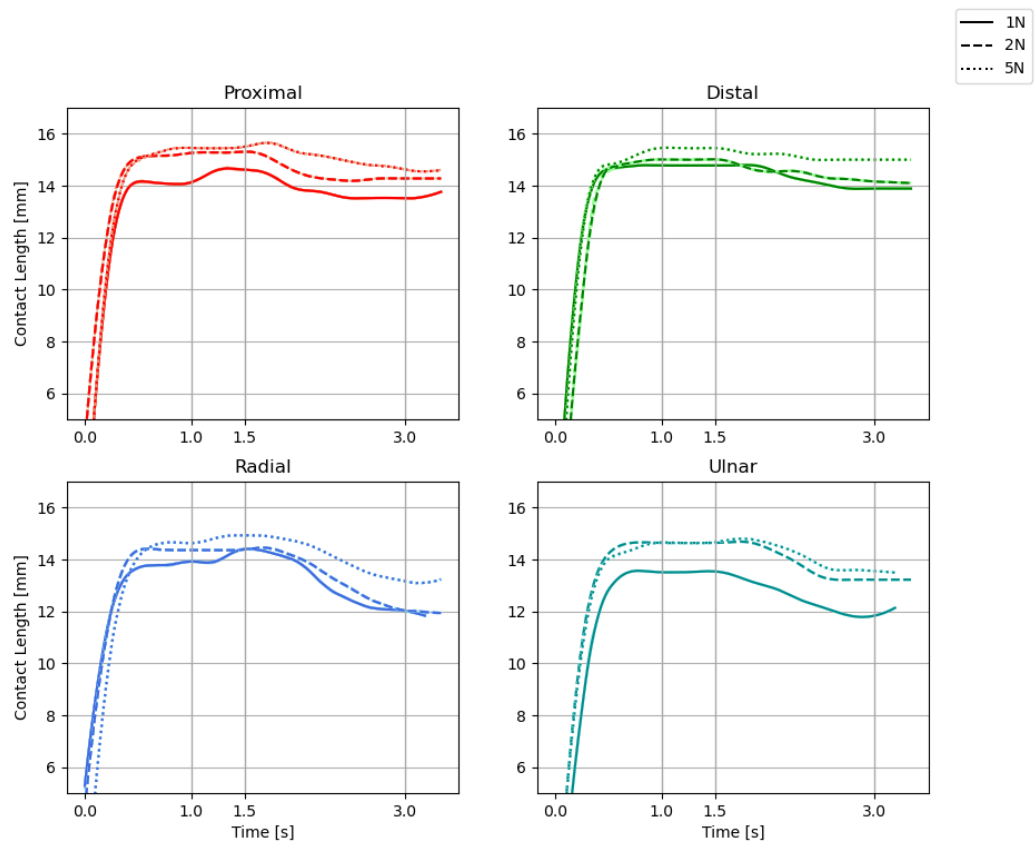


Figure A.2: Contact length for subject S03

Appendix B

Visible Area

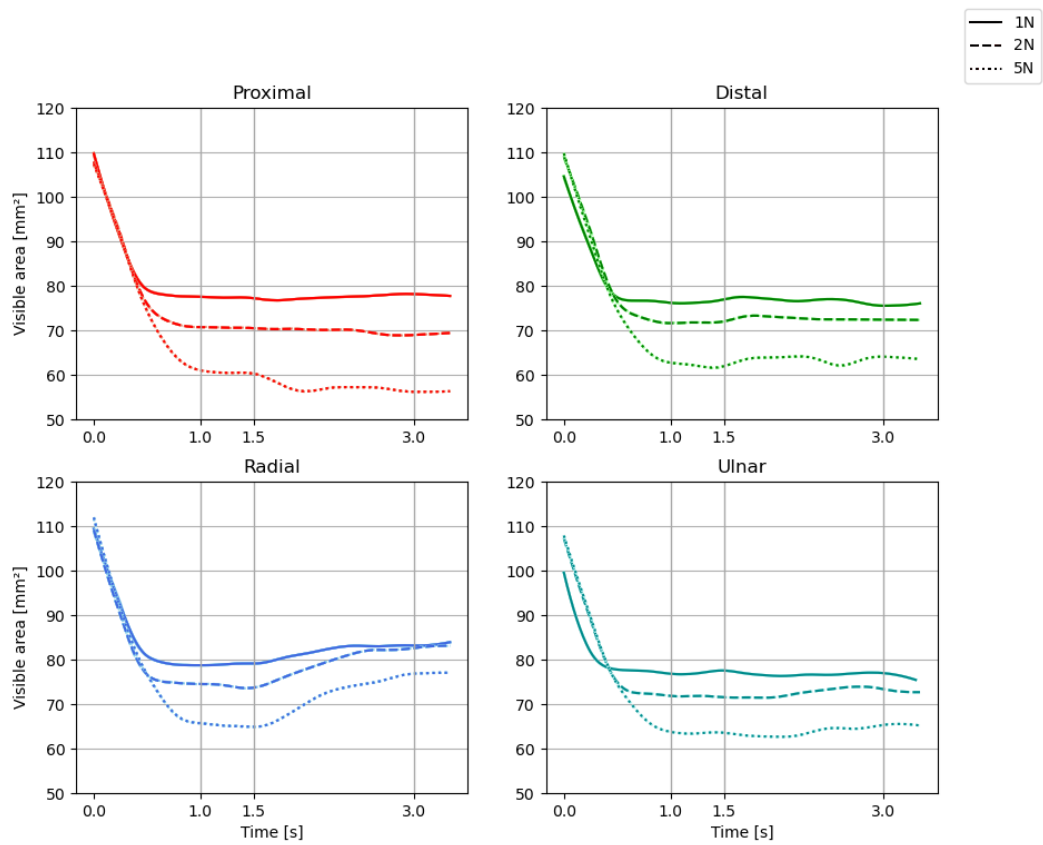


Figure B.1: Visible area for subject S02

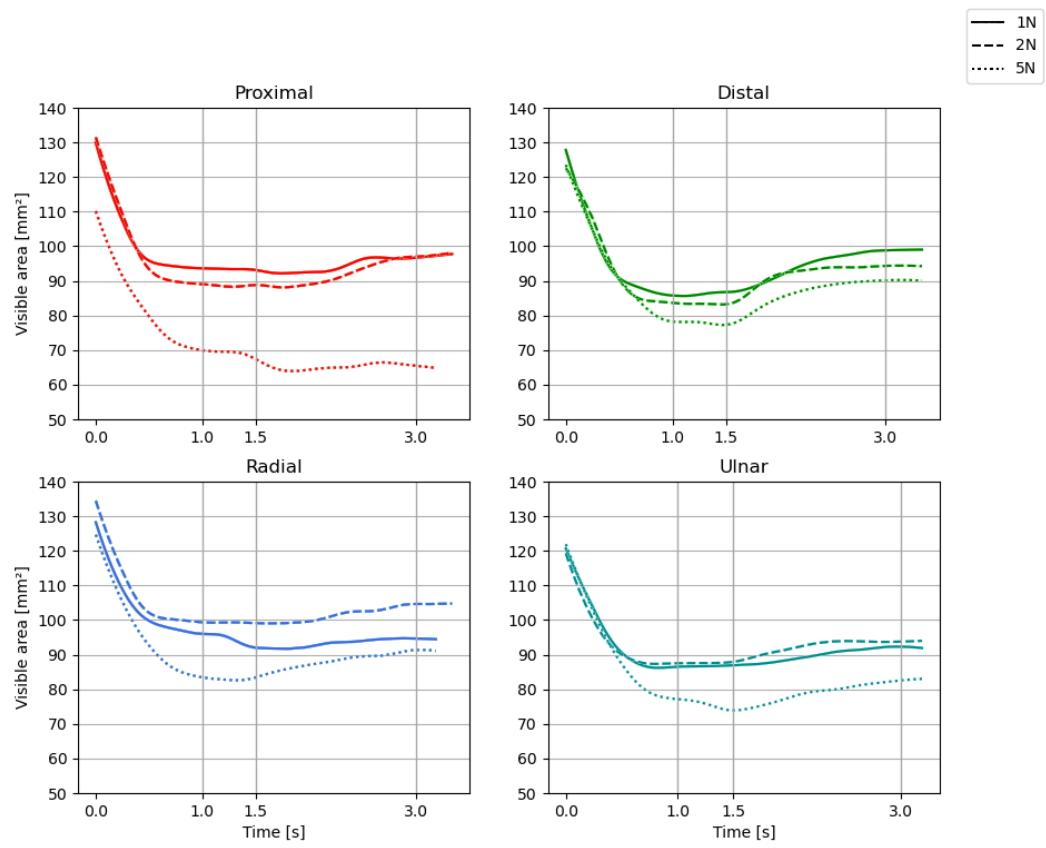


Figure B.2: Visible area for subject S03

Appendix C

Lateral Displacement Field

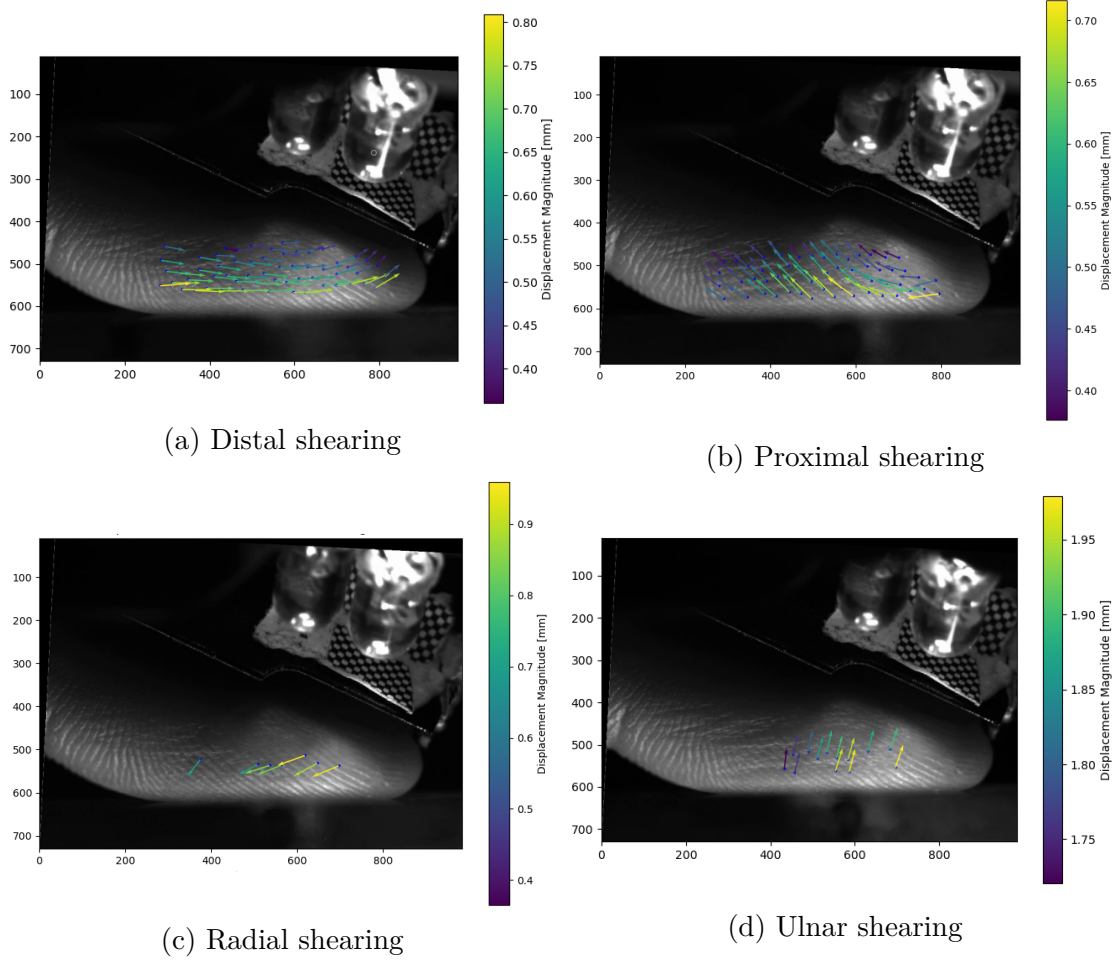
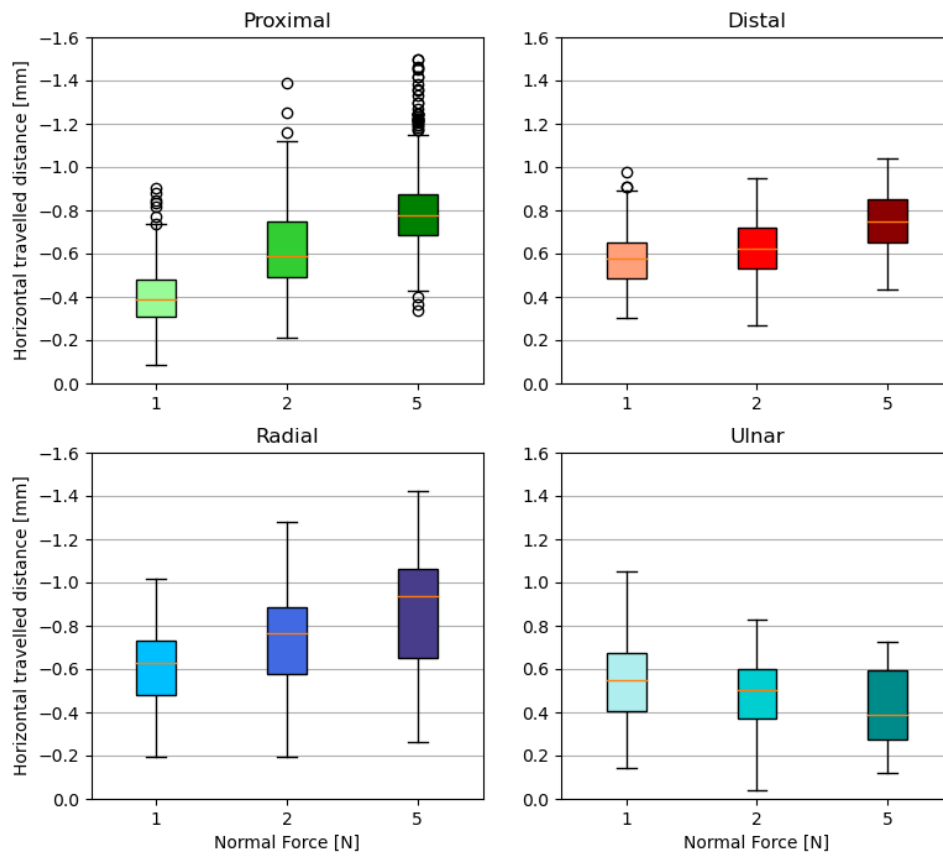


Figure C.1: Lateral displacement fields : example trial for subject S02 at 1N



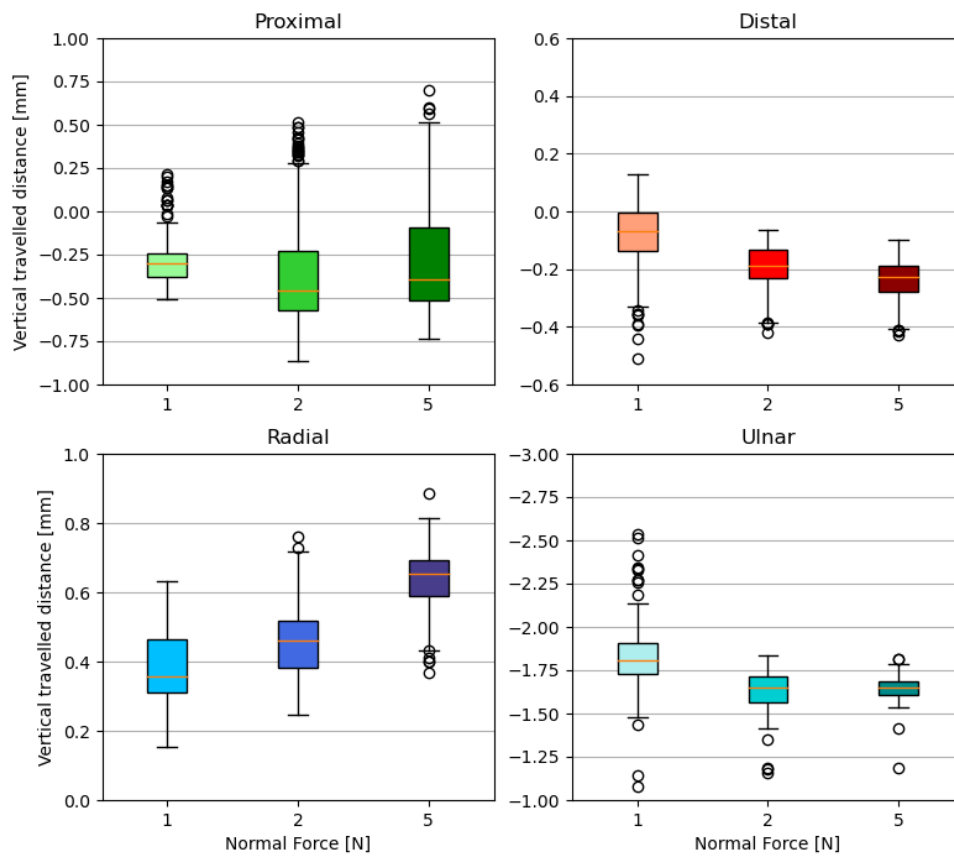


Figure C.3: Vertical displacements for subject S02

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