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Investigation of Wrist Extension Using Three Dimensional Digital Image Correlation

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Abstract Wrist is an extremely significant and important part of our body. It is the performance index of our work. Previous research has shown that wrist flexion can lead to compression of the median nerve in the carpal tunnel, resulting in numbness, parenthesis and muscle weakness in hand. We present an effective optical approach for the measurement of strain on superficial muscles and tendons due to wrist extension, a remedy for carpal tunnel syndrome. The 3D correlation software computes the in-plane and out of plane strain using pictures taken, using 2 charge coupled device cameras, before and after extension. Strain plots obtained after comparison indicates the strain distribution in anterior compartment of the forearm muscle. The experiment is then repeated for four other participants and the trends are observed. The effect of stretching on the two important anterior components of the forearm muscles, namely the flexor pollicis longus muscle, flexor carpi ulnaris muscle is studied. This study can assist practitioners working in the field of applied anthropology to develop advanced diagnosis methodologies.

Keywords: *digital image correlation, wrist extension, flexor pollicis longus muscle*

1. Introduction

Wrist is determinant for optimal performance of the work carried out by a human being [1]. Disciplines such as ergonomics, anthropology and bio-mechanics deal with various aspects of wrist related postures. These disciplines specifically aim at designing job environment to prevent repetitive strain injuries. A great deal of work has been carried out related to the injuries related to the wrist and work environment [2].

Many wrist related hazards have been associated with the occupation of the patient. The disorders can be directly linked with the working environment of the patient as well as with the nature of the work [3]. The injuries related to the wrist are classified as repetitive strain injury (RSI) also known as (repetitive motion disorder (RMD), cumulative trauma disorder (TMD), overuse syndrome). This injury is associated with musculoskeletal and nervous systems resulting from repetitive motions, vibrations, compressions etc.

The primary reason associated with these injuries is the repetitive tasks in the working environment [4]. Risk factors are always co relational and may or may not cause an effect. Occupational risk factors associated with the repetitive tasks in the working environment has been cited regularly. Such inhospitable conditions can cause damage to the tendons passing through the wrist leading to swelling and severe pain. One of the major factors linked to injuries is the swelling of the flexor tendons. Median nerve passing through the wrist is compressed across the carpal tunnel due to swelling.

Median nerve in the carpal tunnel dwelling is surrounded by bones on three sides and a carpal ligament on the fourth side. The tunnel comprises of nine flexor tendons of the hand, passing through the tunnel. The median nerve passing through the carpal tunnel is compressed by decrease in the size of the carpal tunnel or an increase in the size of tissues (swelling) around flexor tendons or both. The median nerve gets compressed as it runs down to the transverse carpal ligament (TCL) resulting into weakness of the flexor pollicis brevis, opponens pollicis, abductor pollicis brevis, as well as sensory loss in the distribution of the median nerve distal to the transverse carpal ligament as shown in Figure 1.

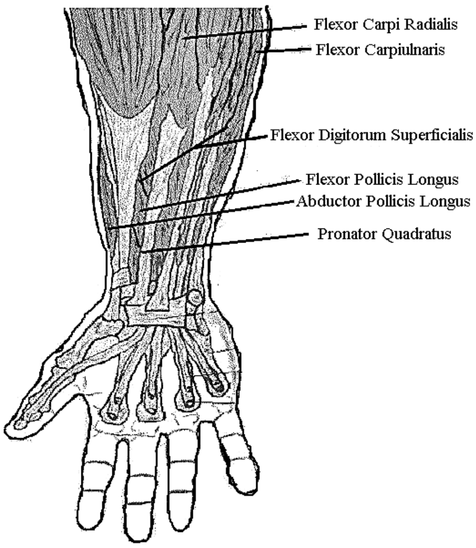

Figure 1. Anterior compartment of Hand

Figure 2. Wrist Extension Experiment: (a) Reference Image (b) Deformed Image

The most important causes of median nerve compression are related with the biological and structural activities rather than the environmental ones [5]. Study performed by Gross et. al., [6] proved the dominance of force as a major risk factor. However Dr. Peter Nathen stated vibrations as the prime risk factor at the American occupational conference in 1996. Genetic predisposition is also considered as a major risk factor. In many parts of the world the medical syndrome results in billions of dollars of worker compensation claims every year [7].

A number of techniques are being used for the analysis and treatment of median nerve compression. The major remedies include splinting or bracing, steroid injection, activity modification, physical or occupational therapy (controversial), medications, and surgical release of the transverse carpal ligament are often used to cure the syndrome. Recent developments in ergonomics have led to changes in working environment in the industries. A number of ergonomic measures have been aimed at preventing median nerve compression. In order to apply the remedies discussed above, it is essential to analyze the strain patter on the wrist. Since the effects of all the factors can be studied by the variations in wrist postures (both wrist extension and wrist flexion), the author aims to come up with a method to analyze the strain field on the superficial muscles and tendons of the top surface of fore arm without any dependence of specialist.

Digital Imagery has being used over a number of years to compute and evaluate strain for a number of applications. 1-d time delay estimation techniques were used initially for displacement and strain estimation [5] while the evaluation of 2-d strain has been developed, using both B-mode data [6] and raw radio frequency (rF) data [8]. These strain-imaging techniques are being used primarily for cardiovascular applications [9] and breast and prostate tumor research [10]. A number of groups have been exploring the opportunity of shear strain imaging and its possible applications [11]. For instance, shear strain imaging has been of interest for characterization of breast tumors [12] and cardiovascular applications [13]. The methodology is also applied for quantitative evaluation of in-plane deformation characteristics of geo-materials [14], and also in medical fields to evaluate local failure of bone [15].

In the past, the measurement of strain was restricted to a specified location or discrete target points in a structure i.e. it was impossible to compute the strain distribution over the whole structure. A number of false attempts were made to extract data at a very large number of locations by using discrete targets due to the time consuming process and computational power requirements. A few techniques such as Moiré Interferometry [16], holographic Interferometry [17], speckle photography [18] have been proposed to acquire the overall deformation contour, but it is often time consuming and involves heavy computational power. On the other hand, Digital Image Correlation (DIC) is a simple and quick state-of-art technique superior to previous techniques due to its ability to compute faster.

DIC was originally introduced in the early '80s by researchers from the University of South Carolina [19]. The idea behind the method was to infer the displacement of the material under test by "tracking the deformation of a random speckle pattern applied to the component's surface in digital images acquired during the experiment" [20]. In addition to its non–contact, non-destructive and full field measurement capability, the 2-D DIC technique is also well known for its simplicity, low environmental vulnerability and easy processing. A large number of algorithms [21] have been developed over the years in order to find the solutions through DIC. Among these methods, the most commonly used algorithm involves an iterative solution that finds the maximum of the cross-correlation coefficient in parameter space [26]. A correlation function is used to calculate the shift between the two images. The algorithm is highly effective when precise displacement between two images have to be calculated. Digital Image correlation has proven to be an extremely effective optical approach with vast applications like determining mechanical properties of human soft tissue in vivo [22], measuring Osteocyte lacunae tissue strain in cortical bone [23], determining local mechanical conditions within early bone callus [24] etc. DIC has been used to analyze the stresses in solder interconnects of BGA packages under thermal loading [25], dynamic testing to study deformation for flexible bodies [27], material characterization at high strain rate [28], stresses and strain in flip-chip die under thermal loading [29] etc.

DIC has been applied multiple times in the past in the field of applied anthropology to assist practitioners for diagnosis [34]. DIC has been effectively used to study the mechanical properties of biological soft tissues e.g. using 2D DIC: on the human tympanic membrane [30], sheep bone callus [32], human cervical tissue [31] and recently also using 3D DIC: for the bovine cornea [32] and mouse arterial tissue [33]. An attempt has also been made to analyse the strain pattern on the wrist using 2D DIC [45].

In DIC algorithm, a correlation function can be used to calculate the shift between the two images taken before and after the deformation by tracking the speckle pattern, leading to evaluation of strain. The computation of cross-correlation can be performed in the physical space [35] or in the Fourier space using Fast Fourier Transform (FFT) [36]. The intermediate cross correlation FFT step can involve heavy computations depending upon the field due to the heavy computational complexity of the speckle pattern [37]. Digital Image Speckle Correlation (DISC) uses digital image correlation to resolve displacement and deformation gradient fields. The underlying principle of DISC consists of tracking a geometric point before and after deformation resulting in its displacement vector.

The aim of the paper is to analyse the wrist extension, through a non-contact optical technique of Digital Image Correlation (DIC). The focus of the experiment is to examine the strain pattern on the superficial muscles of the forearm as result of wrist extension. Wrist extension results in relaxation of the wrist. When the wrist is moved into extension position from flexed position, the carpal tunnel expands resulting into the expansion of the tendons which further leads to the relaxation of the median nerve. The effects of stretching on the superficial components of the arm muscles, namely the flexor pollicislongus tendons, abductor pollicislongus tendons and flexor digitorum superficial tendons in the arm and wrist are studied. This can be of significance in further clinical studies.

2. Digital Image Correlation

Digital image correlation widely used in experimental mechanics [38]. DIC is an application based on comparison of 2 characterized images, with a sequence of analysing gray value distributions establishing the correlation and utilizing the interpolation functions to obtain sub pixel accuracy and displacement of a specific point. Coherent illumination source can be used to illuminate the area of object’s surface and that deformation is obtained over a large measurement range. In 1982 Peters and Ranson first employed DIC for displacement and strain measurement under the assumption that there is a one-to-one correspondence on the intensity pattern of surface images before and after deformation. The idea behind the DIC method is to infer the displacement of the material under test by “tracking the deformation of a random speckle pattern applied to the component's surface in digital images acquired during the exercise” (Lichtenberger & Schreier, 2004). Mathematically, this is accomplished by finding the region in a deformed image that maximizes the normalized cross-correlation score with regard to a small subset of the image taken while no load was applied. This technique is elaborated in Figure 3.

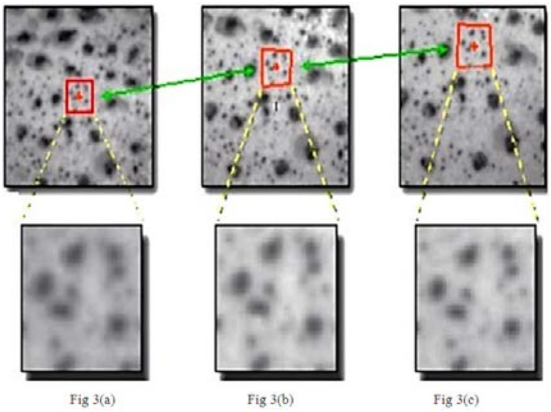

Figure 3. An illustration of DIC showing how the subset changes with deformation with a zooming of the image in the subset

Figure 4. speckle pattern

The Figure 3(a) shows an unstrained specimen with a subset highlighted clearly. On deformation of the material, the changes in the subset can be observed in Figure 3(b). With greater deformation, this is enhanced and clearly observed in Figure 3(c). When this process is repeated for a large number of subsets, full- field deformation data can be obtained. This way, a comparison can be made between the states of the muscles before and after the stretch, using a pre-defined algorithm. In general, when the number of the pixels in the subset is increased, the random error of each correlation function will be decreased with the average effect of the sum. However, it is not true that the lager the subset is, the better the measurement precision is. If the subset size is too large, the calculating speed will be very slow, and the cutting error of the correlation function will be increased. DIC has previously been used in the analysis of deformation of components [39] and its usefulness in biomechanics research has been shown as well.

A large number of algorithms (Sutton, et al. 1986; Schreier, et al. 2000; Chen, et al. 1993; Synnergren & Sjoedahl, 1999) have been developed over the years in order to find the solutions through DIC. DIC has been used in pulse signal detection [40]. DIC has been used for strain measurements in microstructures [41]. DIC has been used to Study displacement measurements [42]. Digital image correlation method is used for measuring in-plane displacements in the presence of high strain gradient [43]. A three-dimensional digital image correlation technique is presented for strain measurements in open-cell structures such as trabecular bone. The technique uses high-resolution computed tomography images for displacement measurements in the solid structure [44].

3. Experimentation

DIC analysis requires a very fine stochastic pattern on the part that is to be analyzed. The experiment is started by coating the body part (right forearm anterior portion with zinc powder in order to provide contrast for better identification of marker points. Later, the zinc coated portion is covered with a random black speckle pattern with a marker. After the stochastic pattern is applied, three dots are darkened, in the region of low strain, to serve as the reference points for the DIC algorithm.

The calibration of CCD cameras is necessary in order to characterize the geometry of the sensors and lenses. The following parameters have to be determined:

1. Intrinsic parameters, such as focal length of the lenses, principle point of the lenses, radial distortions of the lenses, tangential distortions of the lenses

2. Extrinsic parameters, such as translation vector, rotation matrix

In the first step, the intrinsic parameters are determined. A test plate, Figure 5, is manually moved in front of the camera. The camera records different positions of the test plate, which give sufficient data for the complete calibration procedure. The software registers the nodal points of the test blade and automatically captures the different images. Image acquisition takes few seconds and after some more seconds the calibration of the intrinsic parameters is finished.

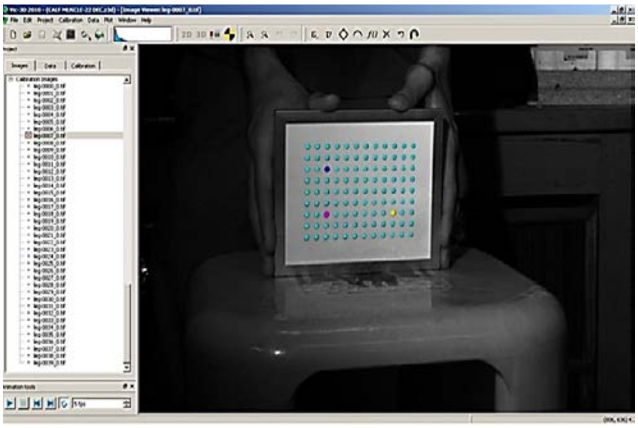

Figure 5. camera calibration

The main parameters such as focal length and principal point are displayed on the monitor for control by the operator. Additionally, the maximum error is displayed. For calibration of the extrinsic parameters the test plate is positioned in front of both cameras, simultaneously. The software is then able to calculate all extrinsic parameters just from this single image.

Five healthy and active males with no muscular disorders participated in the study. No symptoms of fatigue or irritation were noticed during experiment. DIC Experimental setup consists of 2CCD cameras, 2 Illumination light sources, a computer and a tripod stand as shown in Figure 6.

Figure 6. DIC experimental setup

The subject is made to place the forearm at the edge of a table so that view for the camera is not obstructed. Initially the elbow, wrist and palm are aligned in the same plane. The initial relaxed forearm is as shown in Figure 2(a). 2 CCD cameras are used to take the picture, referred to as reference image, of the forearm. In the next step, the wrist is extended by moving the hand approximately 30 degree about the wrist; the deformed image is shown in Figure 2(b). The same setup is used to capture the picture, referred to as deformed image, in the extended position. Finally, the images captured are used for strain computation using VIC 3D software package. The effects of stretching on the superficial components of the arm muscles, namely the flexor pollicis longus tendons, abductor pollicis longus tendons and flexor digitorum superficial tendons in the arm and wrist, are studied.

4. Results

The strain on the superficial muscles of the forearm resulting due to wrist extension is evaluated by DIC using VIC 3D software using the referred and the deformed images. The strain plots show high bandwidth of strain at the two extremes with the strain at central portion of low bandwidth. The overall strain distribution in the forearm muscle increases with increase in inclination.

The subject places the forearm at the edge of a table as shown in Figure 10 with the elbow, wrist and palm aligned in the same plane. 2 CCD cameras are used to take the picture of the forearm in the initial position, referred to as reference image. In the next step, the wrist is extended by moving the hand approximately 30 degree about the wrist. The cameras take the picture of wrist in the deformed position referred to as deformed image. Strain plots obtained indicates the strain distribution in the anterior compartment of forearm. The experiment is then repeated for four other participants and the trends are observed. The simulations are computed on an Intel Core 2 Duo 2.20 GHz machine. It is extremely important as the experiment is an effective remedy for carpal tunnel syndrome

In the experiment, the strain pattern is computed from initial position (reference position) to final position (deformed position) through multiple intermediate steps as shown in Figure 7. The strain distribution in the Abductor pollicis longus, flexor pollicis longus and flexor carpi ulnaris over the whole inclination range is shown in Figure. 8. It is observed from the recorded data that the highest strain in the wrist is recorded for Abductor pollicis longus. In addition, it is interesting to note that the strain distribution is uniform throughout the line a-b as shown in Figure 9. The strain distribution of εxx seems to suggest a fairly uniform strain along the X direction. The distribution at the point proximal to the wrist increases uniformly from one step to the next observed along the line a-b as shown in Figure 9.

The strain is evaluated along a line a-b where point ‘a’ corresponds to the point near to the wrist while point ‘b’ is the farther end on the line a-b of length 184mm as shown in Figure 10. When the wrist is extended the flexor pollicis longus tendons, abductor pollicis longus tendons and flexor digitorum superficial tendons are stretched. The strain field is observed to be maximum at point ‘a’ as the flexor tendons experience the utmost stretch in close proximity to the wrist while minimum at the farthest end of the line at point ‘b’ as the stretch in the tendons goes on decreasing while moving towards the elbow away from the wrist. The statement is supported by the Y- plain strain field plot as shown in Figure 10. The highest strain of 0.021487mm is experienced by point ‘a’ while the strain is minimum at point ‘b’ with a value of -0.0018mm.

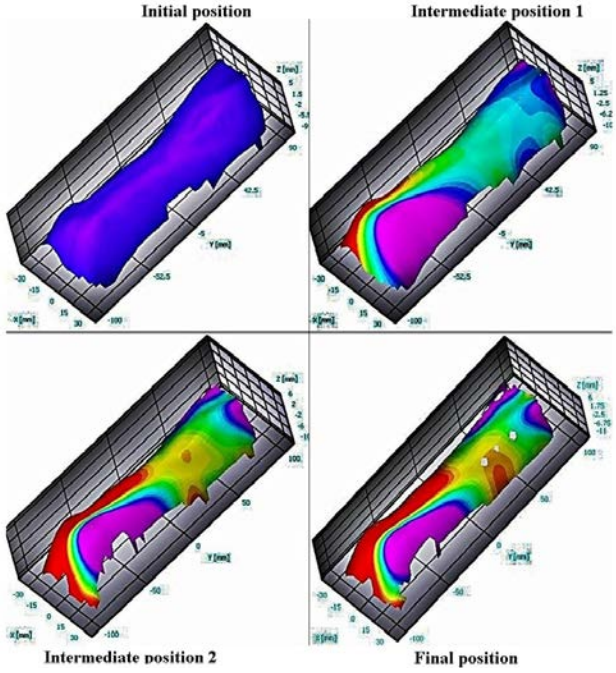

Figure 7. 3D strain distribution at different positions during Wrist extension

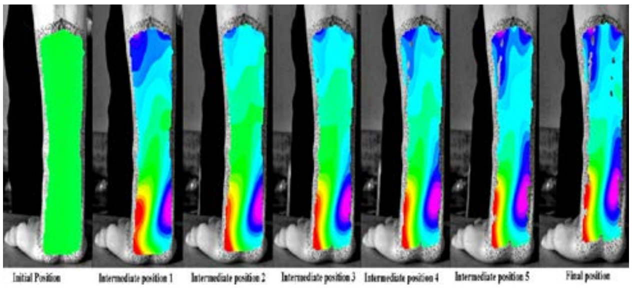

Figure 8. 2D strain distribution at different positions during wrist extension

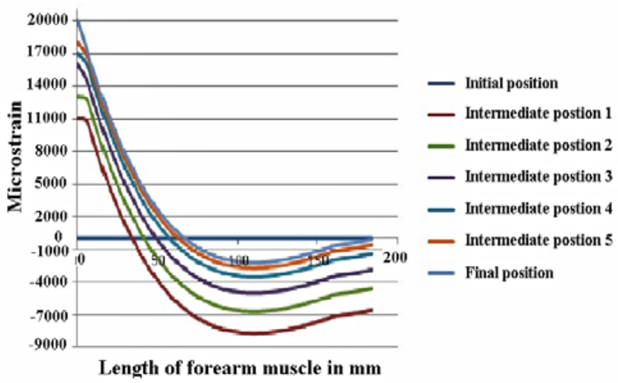

Figure 9. shows the strain variation in the forearm muscle during wrist extension

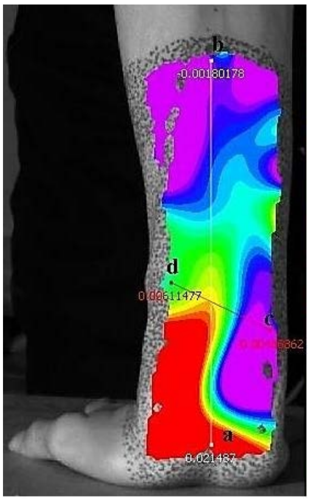

Figure 10. Strain distribution graph on the anterior compartment of the forearm

The strain field along X-plane is computed along X-axis as shown in Figure 10. The strain is evaluated along line a-b formulated such that one end of the line is near the wrist in the area having high strain. The point ‘c’ represents the point near to the wrist while the point‘d’ corresponds to the distant end on the line c-d. The strain field in the X plane is extremely small as compared to the strain field experienced by the tendons in the Y- plane. Point ‘c’ is relatively near to the wrist as compared to point ‘d’ as a result of which thestrain is supplementary at point ‘c’ as compared to the farthest end point ‘d’ along the line c-d. The stretch in the tendons goes on decreasing as we move towards the wrist in the similar way compared to Y-plane. The above statements are supported by the X-plane strain field plot as shown in Figure 10. The highest strain of 0.06mm is experienced at point ‘c’ while the minimum strain at point‘d’ with a value of 0.008mm.

Strain distribution in Y plane computed for wrist extension experiment is shown in Figure 11. Wrist extension is purely vertical or only in Y direction. When the wrist is extended, abductor pollicis longus and Flexor carpi ulnaris are stretched. The strain field is observed to be maximum at point ‘a’ as the tendons experience utmost stretch in the close proximity of the wrist while the minimum at the farthest end of the line at point ‘b’ as the stretch in the tendons goes on decreasing. In the final wrist extended position, the highest strain in Y plane of 0.0255 mm is experienced by point ‘a’ while the strain is minimum at the point ‘b’ with a value of -0.0023mm.

The strain along the X plane is evaluated along a line c-d formulated in a way such that one end of the line is near wrist in the area having high strain as shown in the Figure 12. The point ‘c’ represents the point near to the wrist, while the point‘d’ corresponds to the distant end on the line c-d. The strain field in the X- plane is extremely small as compared to the strain field experienced by the tendons in the Y-plane. The stretch in the tendons goes on decreasing as wrist extension is done in the similar way compared to Y-plane. The highest strain in Y plane of 0.0515mm is experienced by point ‘a’ while the strain is minimum at the point ‘b’ with a value of -0.0049mm. In case of strain evaluation for every feature point CPU computing computed the strain in 54 hrs for wrist stretching experiments respectively.

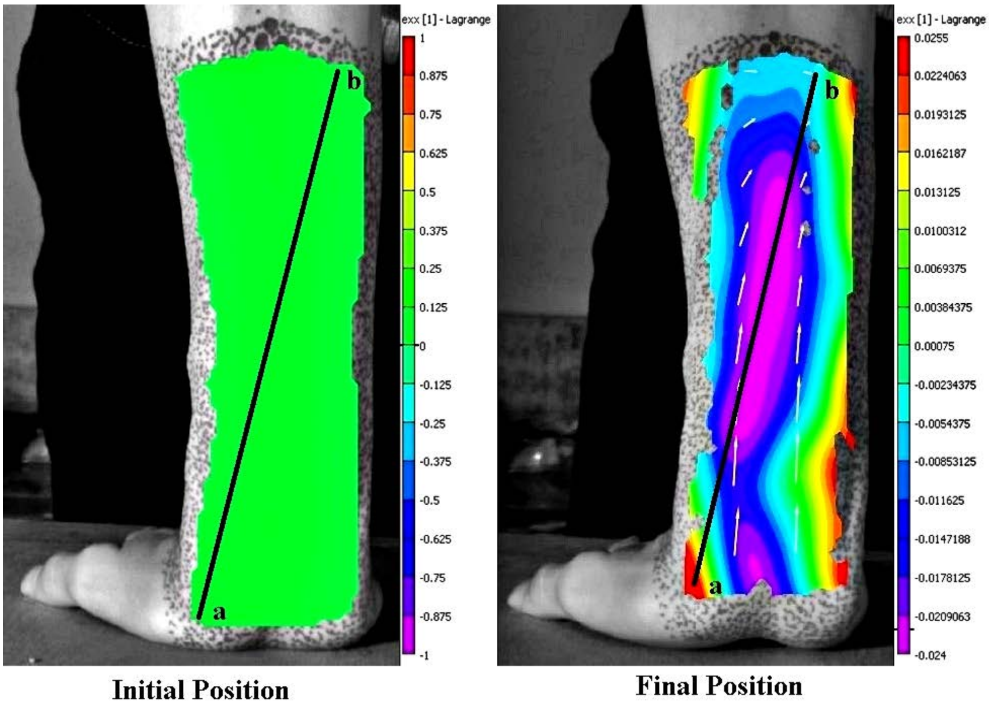

Figure 11. Strain distribution in the X direction at Initial and final position during Wrist extension

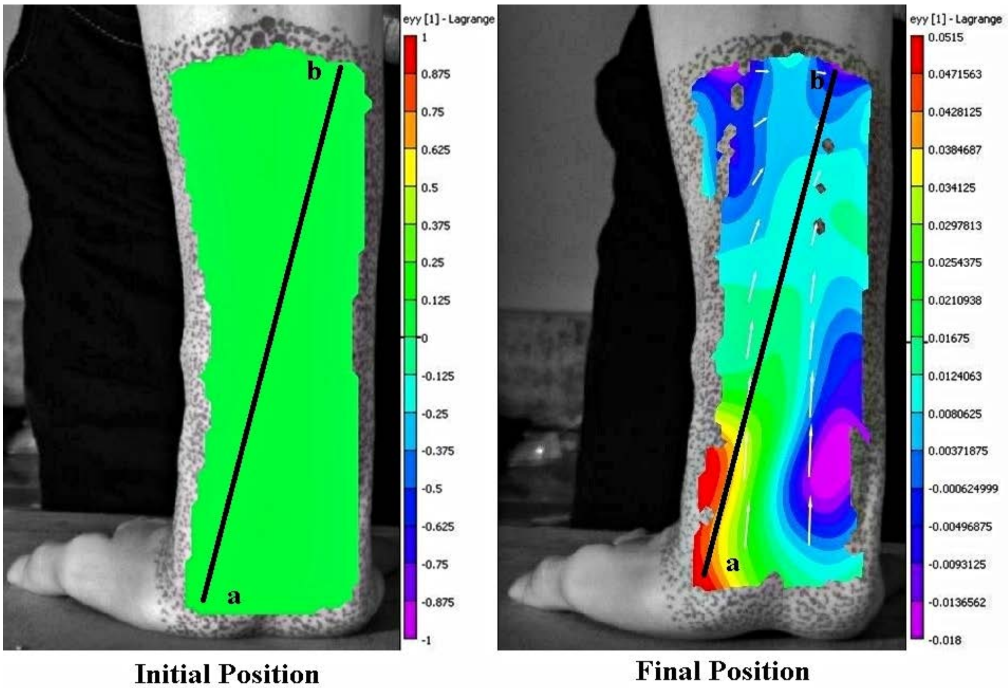

Figure 12 Strain distribution in the Y direction at Initial and final position during Wrist extension

5. Conclusion

The paper presents a generic methodology to compute the strain pattern for wrist extension experiment, a remedy for carpal tunnel syndrome. It is extremely important as well as essential to understand the contraction and elongation behavior of the superficial flexor tendons with respect to the force applied on the wrist as the primary knowledge gained will assists us to generate muscle-tendon units which can resulting into better understanding of the force and energy production. The simulations can be further used to get relevant information regarding input parameters for simulation models of the human system as well as to examine adaptation phenomena of tendons and aponeuroses to physical activity. This system will also help physiotherapists, surgeons and practitioners to educate themselves and refine their work related to median nerve compression. The study will finally play a vital role in avoiding median nerve compression.

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