AN ANALYSIS OF LEG MUSCLE STRETCH USING DIGITAL IMAGE CORRELATION

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ABSTRACT

This experiment aims to examine the strain in the leg muscles when subjected to varied degrees of stretch using the technique of Digital Image Correlation (DIC). This test requires the subject to stand on a variable slope and images are captured at varying inclinations of the slope. The images are then analysed using a DIC software package which compares the images captured before and after the stretch. Through this comparison, strain plots are obtained that indicate how the strains in the calf act along the entire region of study. A comparison of the effects of varied inclinations is made. The experiment is then repeated for five other participants and the trends are observed. The effect of stretching on the two important superficial components of the leg muscles, namely the gastrocnemius muscles and the Achilles tendon, is studied. From the research, the strain distribution in the leg can be understood easily, which in turn helps in understanding the superficial muscle behaviour as well. It is also suggested that DIC can be an extremely effective non-contact analysis tool in biomechanics research.

Keywords*:* Digital Image Correlation, Calf Muscles, Achilles tendon, Gastrocnemius Muscles, Vic-2D

INTRODUCTION

The leg muscles are among the most heavily used in the human body and injuries to the muscles as a result of heavy exertion are an area of great concern. Be it the athlete or the driver, the leg muscles constitute an area that is easily prone to injury. Calf muscle is considered as the bottom heart of the body, due to its capability to pump blood back up to the heart. During period long stance the blood flowing in the bottom portion of the leg will not have enough pressure to pump up to the heart. This results in clotting of blood in the calf muscle and this is known as Deep Vein Thrombosis (DVT). Although blood clots are inherent characteristic of human which tries to prevent bleeding, blood clots will become dangerous when precautions are not taken. Proper exercises are known to mitigate some of these problems and it is very important to understand the effect of an exercise on these muscles. This helps to evaluate the efficacy of various exercises. This paper explores a non-invasive method based on digital image correlation to understand the behavior of superficial muscles of the leg in response to a particular stretching.

Fig 1 gives a superficial view of the posterior leg muscle. The gastrocnemius muscles and the Achilles tendon, in particular, have been identified as the key components in the leg. A great deal of research has been done on the roles of these muscles and their interactions during everyday activities like walking, running and climbing stairs (Lichtwark & Wilson 2006; Wallenbock, Lang & Lugnert, 1995; Sanderson, et al. 2006). Anatomically, it has been shown that a stretch of the leg muscles, particularly the gastrocnemius muscles, have a great impact on the Achilles tendon (Spanjaard, et al. 2008).

The gastrocnemius is located with the soleus in the superficial posterior compartment of the leg. It originates from the posterior (back) surfaces of the distal head of the femur. Its other end forms a common tendon with the soleus muscle; this tendon is known as the calcaneal tendon or Achilles tendon and inserts onto the posterior surface of the calcaneus, or heel bone. *The Achilles tendon* goes from the back of the heel up toward the back of the leg where it connects to the large muscles in the calf of the leg.

Proper stretching can help this complex leg musculature to remain healthy. The act of stretching, itself has been shown to be advantageous in various activities like warming up, improving flexibility (Ferber, et al. 2002), and to prevent injury (Wilson, et al. 1991). This paper attempts to gain an understanding of the behavior of the leg muscles when subjected to a simple stretch, induced by virtue of foot dorsiflexion. We use DIC (Digital Image Correlation), a non-contact technique, to measure the resulting strain distribution in the leg muscles.

This paper neglects the curvatures in the leg and does not consider any out-of-plane displacements in the analysis. Appropriately, the application of DIC to the leg muscles is approximated to a 2-D analysis.

The objectives of this paper are:-

- To point out the applicability of DIC in biomechanics research
- To provide an understanding of the strain distribution in the leg muscles subjected to foot dorsiflexion
- To gain an understanding about a very popular Iyengar yoga prop – the calf slope.

This paper shall go on to examine each of the above objectives in order, starting with a brief purview of the DIC technique.

DIGITAL IMAGE CORRELATION

DIC is a non-contact optical technique that allows the full-field estimations of strain on a surface under an applied deformation. DIC has previously been used in the analysis of deformation of components (Gi Jeung Um & Hyoung-Jin Kim, 2007; Abanto-Bueno & Lambros, 2002) and its usefulness in biomechanics research has been shown as well (Wang, et al. 2002, Nicolella, et al. 2006, Hoc, et al. 2006, Thompson, et al. 2007). In this paper, we analyze the leg muscles using DIC.

DIC was originally introduced in the early '80s by researchers from the University of South Carolina (Peters & Ransom 1982). The idea behind the 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 **Fig 2**. The Fig-**2-a** shows an unstrained specimen with a subset highlighted clearly. On deformation of the material, the changes in the subset can be observed in Fig-**2-b**. With greater deformation, this is enhanced and clearly observed in Fig-**2-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.

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. Among these, the most commonly used algorithm involves an iterative solution that finds the maximum of the cross-correlation coefficient in an n-dimensional parameter space.

While the technique of DIC can be understood pretty easily, it is also essential that one understands the strains that are measured using DIC. DIC primarily measures three types of strain, the X-strain, the Y-strain and the Principal Strains. The Principal strain is a combination of the X-strain & the Y-strain. The stretch due to dorsiflexion is theoretically believed to be vertical (O'Donovan, et al. 2006). This implies that the X-strain should be fairly constant. Similarly, the principal strains 1 & 2 are dependent on the principal stresses in the X & Y direction. So, theoretically, if the X-strain is constant, it is assumed that the principal strain plots will be similar to the strain plots of the Y-strain. This paper attempts to show that the strain plots obtained through DIC will corroborate with the plots expected theoretically.

VALIDATION OF DIGITAL IMAGE CORRELATION

Digital Image Correlation Technique of Full Field Strain Measurements has no standards and hence experiments are carried out to validate DIC Measurements.

The experimental set up is shown in **fig 3.** For these experiments the test specimen is a typical photo elastic model and is made out of acrylic sheet of 0.5 mm thick. The strain field of the test specimen is available in literature. Photoelastic fringe pattern provides difference of principal strains (ε_1- ε_2). But for the fringe pattern for the selected test specimen would be the same for either ε_1 or $\varepsilon_{yy.}$ Qualitatively the DIC results are compared with photoelastic strain patterns and quantitatively with strain gage measurements. A speckle pattern is applied on the test specimen on the front side. A strain gage (350 ohms, Quarter Bridge) is bonded at the centre on the back side of the specimen. The specimen is mounted on a test rig. The strain gage output is connected to SCAD 500 – strain measurement system. The strain data is viewed on the front panel LCD (liquid crystal display) of SCAD 500 and also on the host pc via RS 232 interface. The test rig has a thumb wheel and rotation of the wheel in clockwise direction introduces tensile strain and anticlockwise rotation introduces compressive strain. The images are captured using 5 mega pixel digital camera.

Loading Pattern:-

The test specimen is mounted in the test rig. A tensile load is applied by rotating the thumb wheel till the SCAD 500 shows a strain value of 2000 $\mu\varepsilon$. At this stage an image is captured. Subsequently images are captured in increments of 2000 $\mu\varepsilon$ up to failure of the test specimen. The image correlation and displacement & strain analysis is done in correlated solutions VIC– 2d software the DIC measurements compared extremely well with the photo elastic fringe pattern and strain gage measurements. DIC results also showed excellent linearity.

Results are presented in **Fig 3**

Yoga prop for calf stretch

This test requires an Iyengar yoga prop to provide the variable slope, which in turn causes varied degrees of stretch. The Iyengar yoga prop is essentially a wooden plank whose angle can be varied upto a certain limit in steps so as to provide variable slope. **Fig. 4** shows the model of the equipment used in this experiment. This model has been constructed using the Solidworks software and gives an isometric view of the equipment. The inclined plate is movable in conjunction with the main plate and the rod can be fitted into any one of the holes so as to obtain the desired inclination. At every degree of stretch, the images are recorded with a digital camera. Following that, these images are analyzed using a DIC software package (Vic2D, Correlated Solutions, West Columbia, SC) to find the strains and the resulting strain plots.

METHOD

The primary requirement for a DIC analysis is a very fine stochastic pattern on the part that is to be analyzed. The DIC method does not require the use of lasers and the specimen can be illuminated by means of a white-light source. However, the specimen surface must have a fairly uniform random pattern, which can either be naturally occurring or applied to the specimen before the test. Among the many methods or pattern application are self-adhesive, pre-printed patterns, stamps and application of paint speckles with air-brushes, spray cans or brushes. In this study, a white paint used by theatre artists is applied on one of the legs and the speckle pattern using black paint is superimposed on the white paint. 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.

Six healthy and active males with no known records of neural/muscular/skeletal disorders participated in the study. Informed consent was obtained from each participant before the experiment was conducted. The average age, body height and body mass of the participants are 35.5 years, 170 cm and 68.5 kg respectively. The participants did not report any pain, fatigue or other problems during or after the experiment. The subjects were able to wash the paint easily and did not face any problems of itching or irritation after the experiment.

The calf slope, which helps provide varied degrees of stretch is kept against the wall. In this experiment, the inclinations used are 0, 7, 12, 18, 24, 30, 35, 40 and 45 degrees. In order to capture the image of the unstretched calf, the slope is set at zero degrees. A reference point is marked on the calf slope, so that the foot is placed at the same point at every inclination. The subject is asked to stand on the slope with his painted leg, while keeping the other leg folded up in the air. The camera is placed at a fixed distance from the subject and focused on the painted leg to obtain a clear photograph with optimal brightness. Following this, an image of the un-stretched calf is captured. This image serves as the reference for further analysis.

Then, the calf slope inclination is increased to the next angle. The subject is asked to stand on the slope in a similar manner as above. It is essential that before the image of the stretched calf is captured, the straightness of the leg is ensured. The subject is made to stand for 30 seconds and then the image of the stretched calf muscle is taken. This step is repeated for all the angles. Once images are captured, they are then analyzed using a DIC software package

RESULTS

Fig 5-a and **Fig 5-b** shows the Y-strain plot of captured images. **Fig 5-c, 5-d** shows the X-strain plot and the Principal Strain plots at the highest tested angle of 45.6°. **Fig. 5** indicates the distributions of strain throughout the length of the leg at various inclinations. The lines in the graph represent the strain along the line indicated in **Fig. 5** (the line drawn from the point proximal to the knee to the point at the base of the foot, i.e. the point of insertion of the gastrocnemius muscles to the point of insertion of the Achilles tendon into the heel bone) considered as the Y co-ordinates.

The strain plots show very high bandwidths of strain at the two extremes with the strain at the central portion being of low bandwidth. The overall strain in the leg muscles increases with the increase in inclination. More interestingly, with greater stretch, the strain plots too show greater uniformity. The strain at the point proximal to the knee increases from one angle to the next. This trend interestingly is not shown at any other point in the leg. While that can be said about the leg muscles as a whole, when one delves into the details of the gastrocnemius muscles and the Achilles tendon in particular, many interesting observations can be reached.

The profiles of the Y-strain as well as the Principal strain clearly show that with the increase in inclination, the strain at the start of the gastrocnemius muscles clearly increases from one step to the next. At lower inclinations, the strain increases uniformly along the entire length to reach its peak at the point proximal to the heel. At higher inclinations the strain at the start of the gastrocnemius muscles is high and the strain dips till about midway and then rises to reach its peak at the point proximal to the ankle. This clearly indicates that the point where the line begins, i.e. the start of the gastrocnemius muscles is a key area that can be subject to quite a sizeable amount of strain during the leg muscle stretch.

The highest strain in the leg muscles is seen to be at the point of insertion of Achilles tendon into the heel bone. This peak strain though does not increase uniformly. In fact, this strain decreases after a certain threshold which is seen to vary from one individual to another. This threshold angle can be said to be dependent on the inherent characteristics in the human calf of the person under study.

The strain distribution of ε_{xx} seems to suggest a fairly uniform strain along the X-direction. The distribution of Principal Strain 1 also shows a similar result. Another interesting observation is that the Y-strain plot shows negative values at the lower strains, while the

Principal strain plot does not show any negative strains at all. This suggests that the X-strain has a positive value that is nearly constant throughout.

For one of the participants in the study, the angle of inclination could not exceed 39°. In other words, this was the maximum stretch his leg could be subjected to. This leads to the observation that the strains in the leg muscles vary from one person to another based on the pathological conditions in the leg. However, the nature of the graphs and the strain plots shown in **Fig. 6** remain the same for all the participants. **Fig. 7** has been attached as a proof of that statement. Another added proof to this statement is that the value of the strain in the leg remained within the range of 0.02 to 0.3 for all participants.

To summarize, the stretch that is observed in the calf can vary from one person to another. Yet, the general trends described above are applicable to all.

DISCUSSION

A quick glance at the strain plots (**Fig 5a-5d**) suggests that the Principal strain plot follows a similar path as the Y-strain plot. This seems to suggest that the X-strain is constant and that the stretch is purely along the Y-direction. Now, this supports the theoretical belief that the stretch during dorsiflexion is purely vertical. This corroboration proves the veracity of the DIC technique.

At the lower degrees of stretch, it is seen that the Achilles tendon takes the bulk of the strain, while very little strain is seen on the gastrocnemius muscles. At higher inclinations, what happens is quite the contrary. The gastrocnemius muscles seem to be exhibit a very high strain in comparison to the Achilles tendon. To rephrase the same, the Achilles tendon takes the bulk of the strain at a lower degree of stretch. However, while one increases the degree of stretch, the gastrocnemius muscles too are strained to a considerable extent while the strain at the Achilles tendon persists. This seems to suggest strain redistribution among the calf muscles as the inclination increases.

Previous research on the Achilles tendon has shown that the "overall load on the Achilles tendon increases when the gastrocnemius/soleus muscles are activated to a greater extent" (Wallenbock, et al. 1995). It is also known that when muscles are activated, the principal strain in the muscles increases. It has also been shown that the strain at the point of insertion of the gastrocnemius muscles increases with inclination. One can clearly infer from the same that with greater inclination, the activation of the gastrocnemius muscles increases. The above facts clearly yield the inference that with greater stretch, the Achilles tendon is more strained and consequently, the chances of rupture are greatly increased.

While data is easily obtained on the effects of this exercise on the Achilles tendon, the role of the gastrocnemius muscles should not be neglected at this point. To begin with, these muscles have a huge role to play in the gradient that is obtained in each plot. As has already been highlighted, these muscles take up greater amounts of strain as the angle of inclination increases. That apart, at lower inclinations, the strain in these muscles increases uniformly along the line, whereas at higher inclinations, the strain is high at the point where the muscles begin, and thereafter there is a continuous dip. This interesting observation could perhaps be explained by the following hypothesis.

At higher inclinations, it is possible that the presence of tension at both the ends causes the strain at the central portion of the calf muscles to be minimal. This can be compared to a beam that is subjected to high tension at both its ends, causing very high deformation at the ends, with little effect at the central portion. This could well be the reason for a very narrow bandwidth of strain at the central portion of the leg (indicated in Fig. 3) with very high bandwidth of strain at the extremes.

Finally, this research has been approximated to a 2-D analysis without considering any planar deformations or out-of-plane displacements. Hence, this paper required the use of DIC purely as a 2-D application. However, recent research seems to suggest that DIC can be used just as effectively with multiple cameras, permitting the measurement of three-dimensional shape as well as the measurement of the three-dimensional deformation.

CONCLUSION

The experimental studies repeated show that DIC can be a useful technique of analysis in the field of biomechanics research. The numerical values and the plots of strain obtained clearly indicate the importance of the Achilles tendon and the gastrocnemius muscles in the anatomy of the calf. The uniform increase of strain as well as the uniform strain distribution at higher inclinations serves as a clear indicator as to how an inclination of the foot can lead to great strain on the Achilles tendon. Furthermore, this research serves to give a clear understanding of the superficial muscle behavior through the strain plots. Henceforth, it is possible that one can estimate the nature of muscle behavior just by understanding the points of high strain during the exercise.

FIGURES

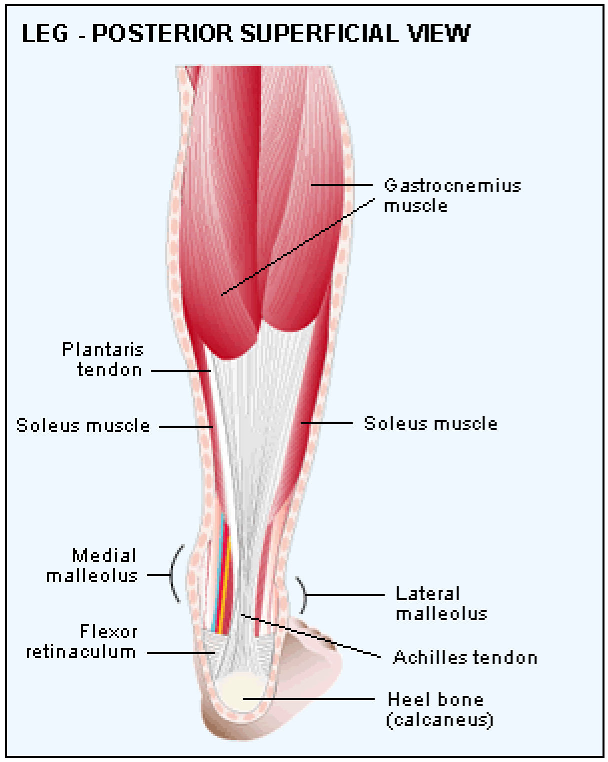


Fig 1: Posterior Superficial view of the leg

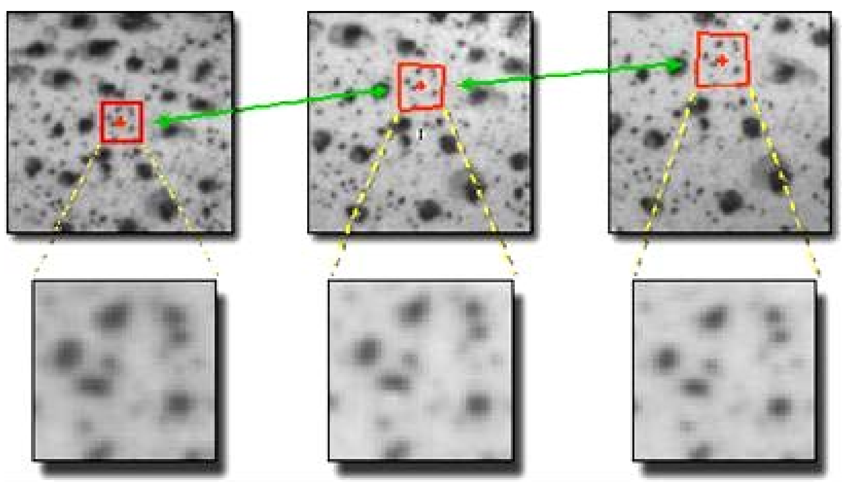
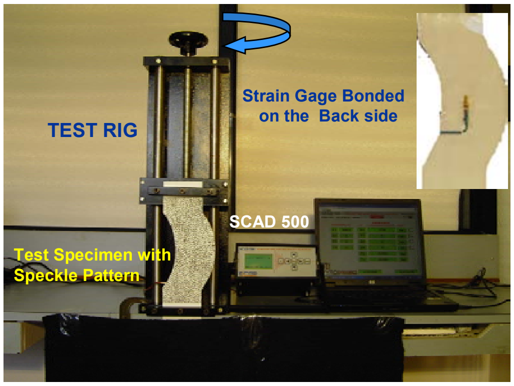


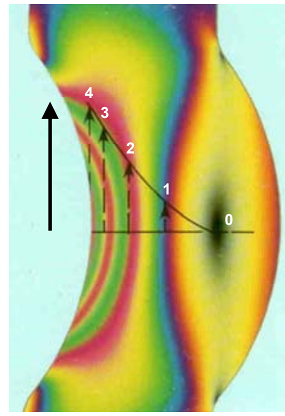
Fig2a **Fig2b** **Fig2c**

Fig 2 – An illustration of DIC showing how the subset changes with deformation with a zooming of the image in the subset

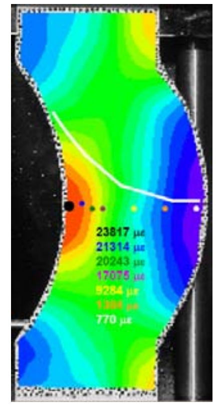
Fig 3 – VALIDATION OF DIGITAL IMAGE CORRELATION



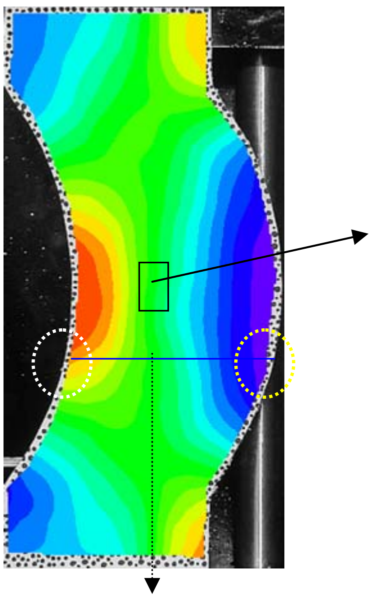
Experimental Set up

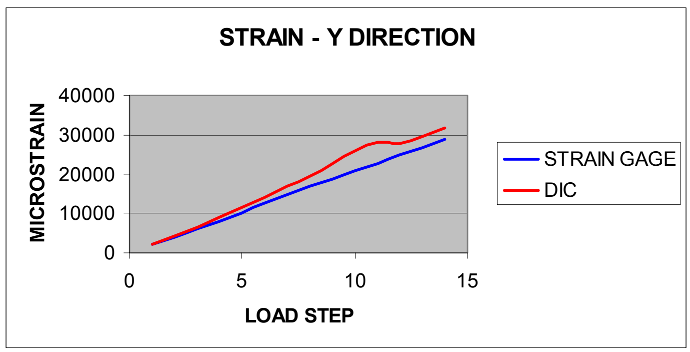


Photoelastic fringe Pattern. The pattern has a fringe order of 4 at the left side Edge & has the highest Strain. The lowest strain is at the right side edge Fringe order 0.

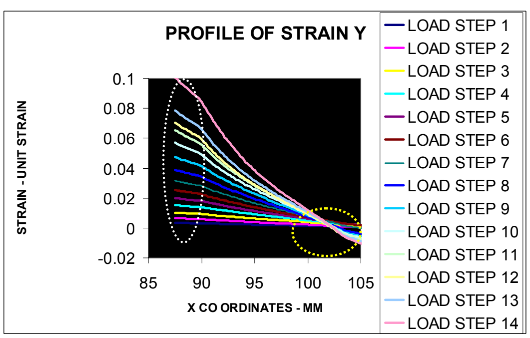


DIC pattern (ε_{yy}) at Load Step 3 (6000 με).

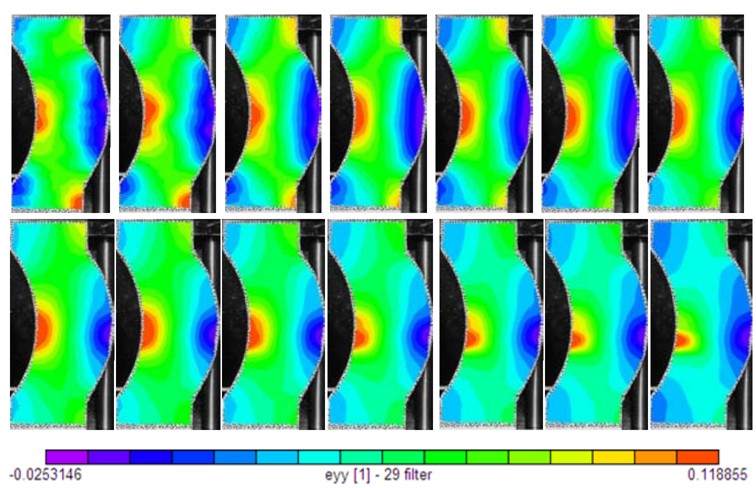




Comparison of DIC patterns (ε_{yy}) with strain gage measurements.



DIC patterns (ε_{yy}) at various load steps upto failure.



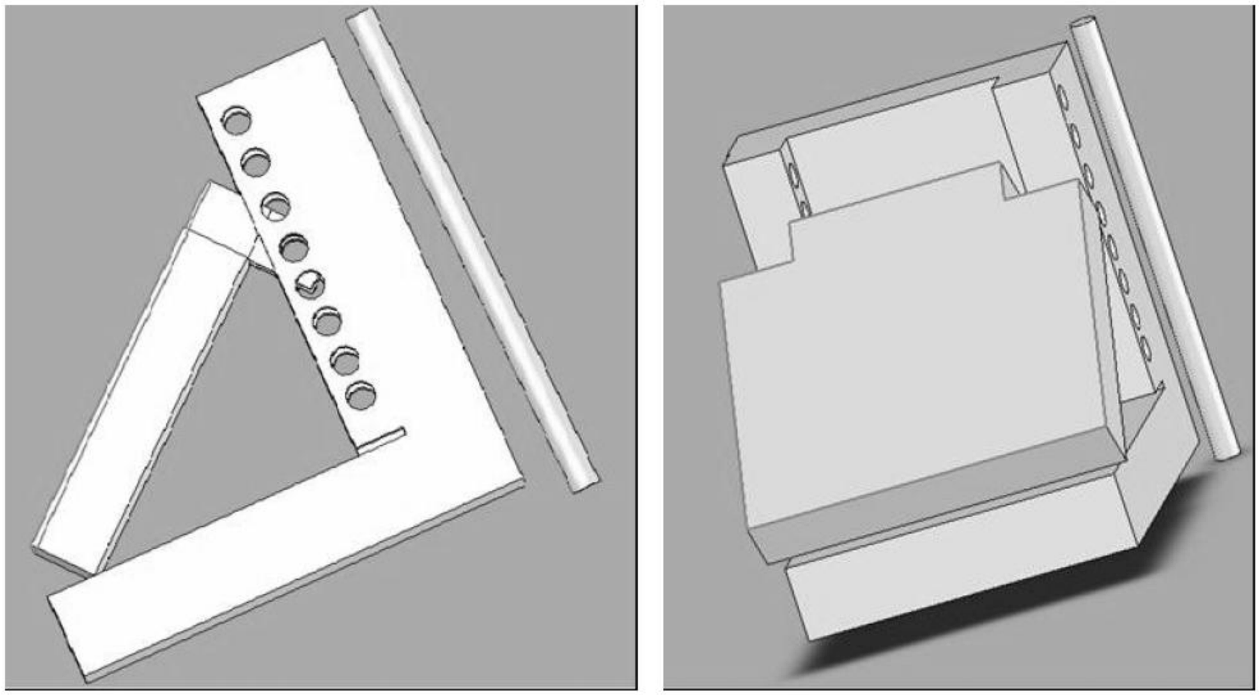
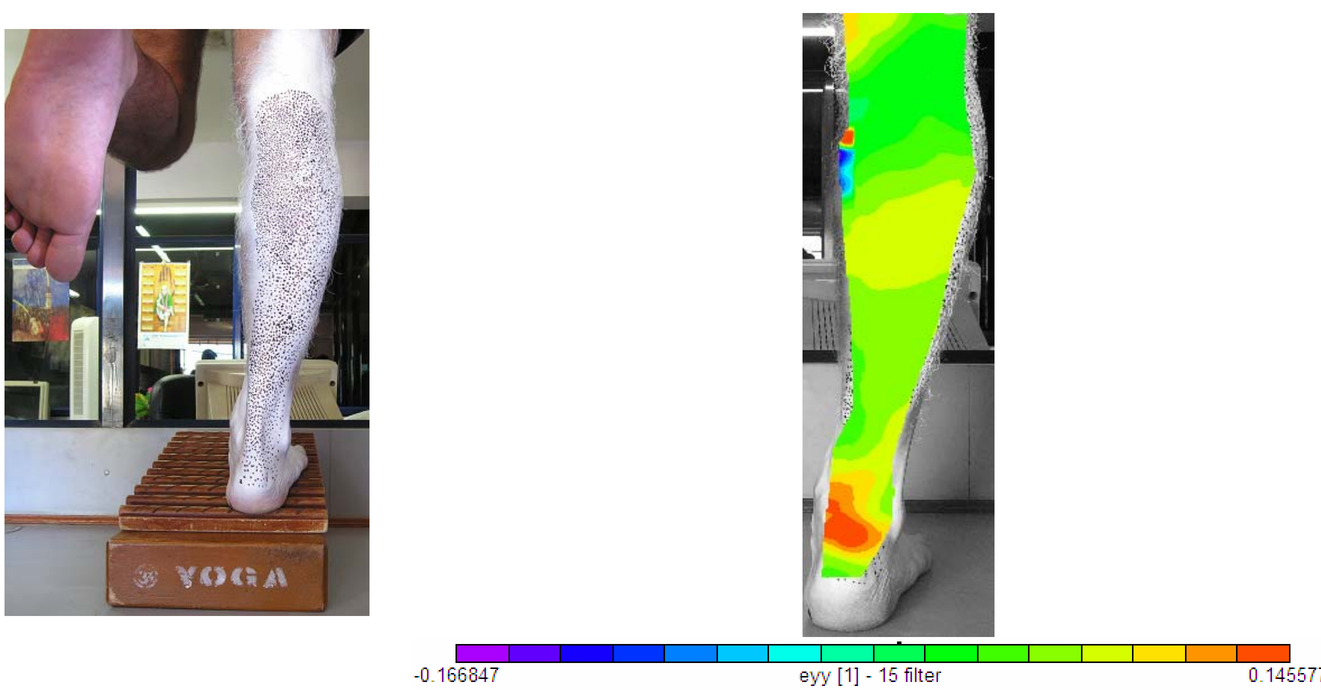
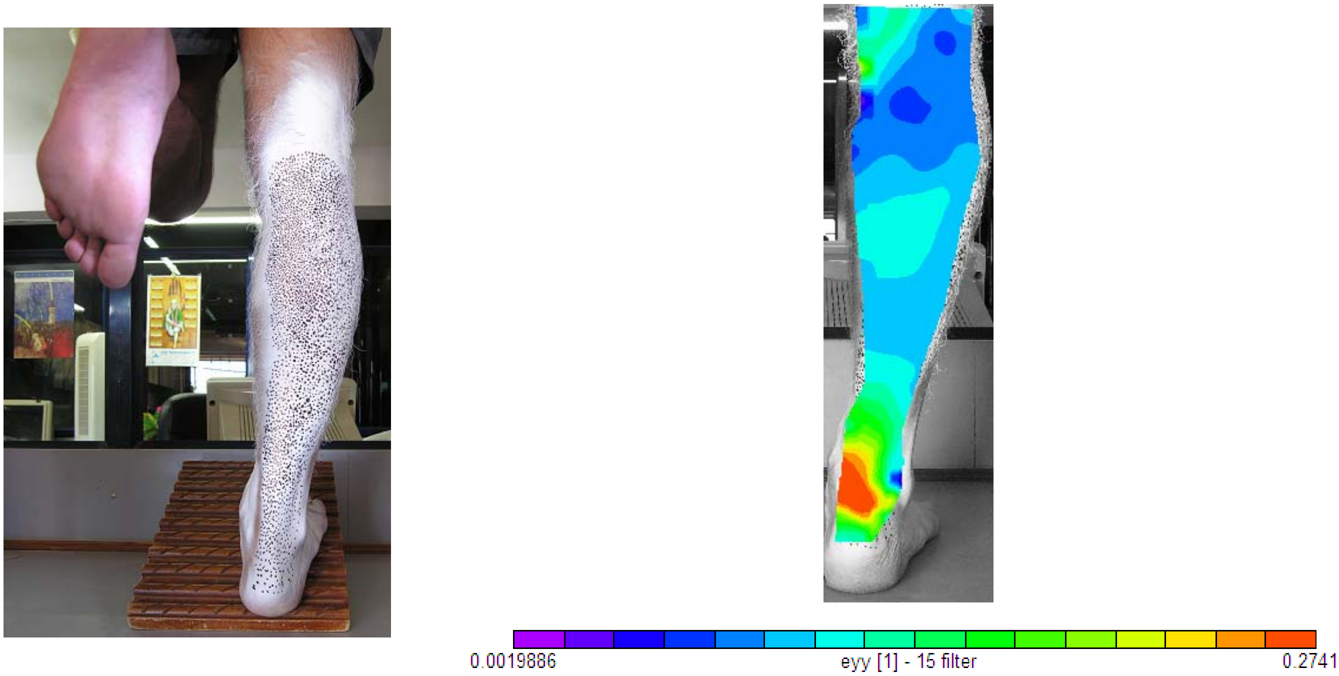


Fig-4 Yoga prop for calf stretch



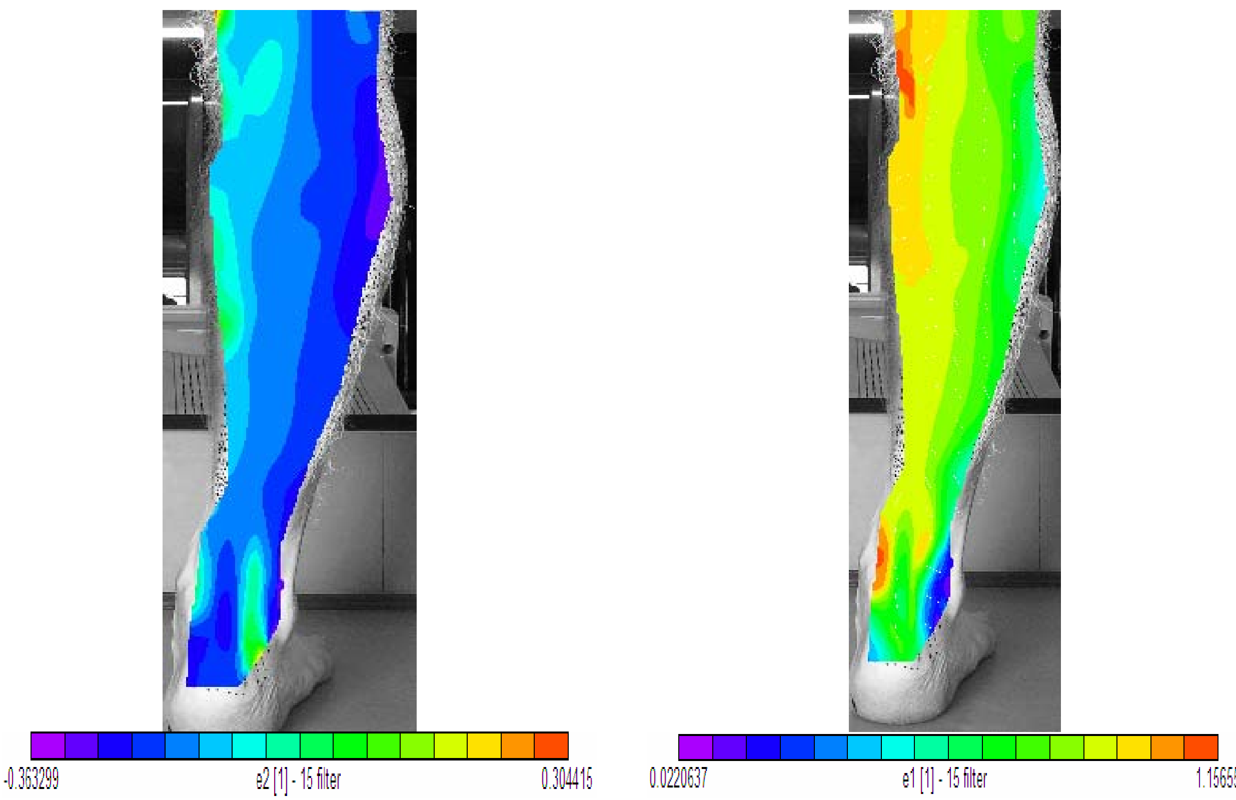
Strain units –Unit Strain

Figure 5-a Strain Pattern in the Y Direction at 11.8 Deg Inclination



Strain units – Unit Strain

Figure 5-b Strain Pattern in the Y Direction at 24.2 Deg Inclination



X-strain plot Y- strain plot

Figure 5-c Principal Strain X and Y at 45.6 Deg Inclination

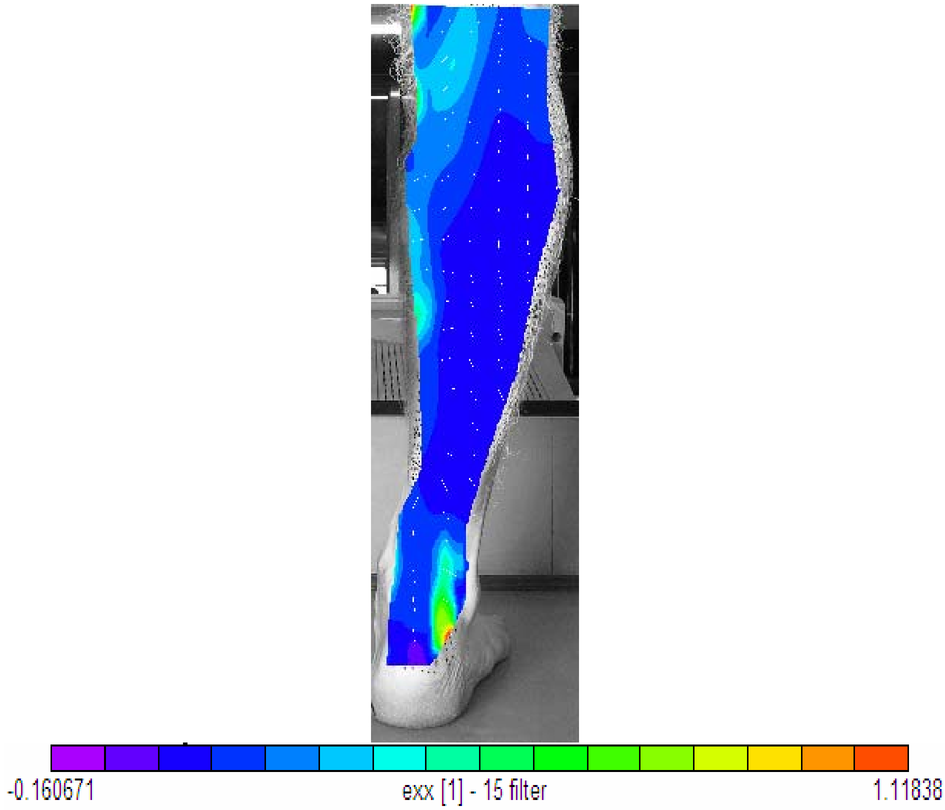


Figure 5-d X-Strain ε_{xx} at 45.6 Deg Inclination

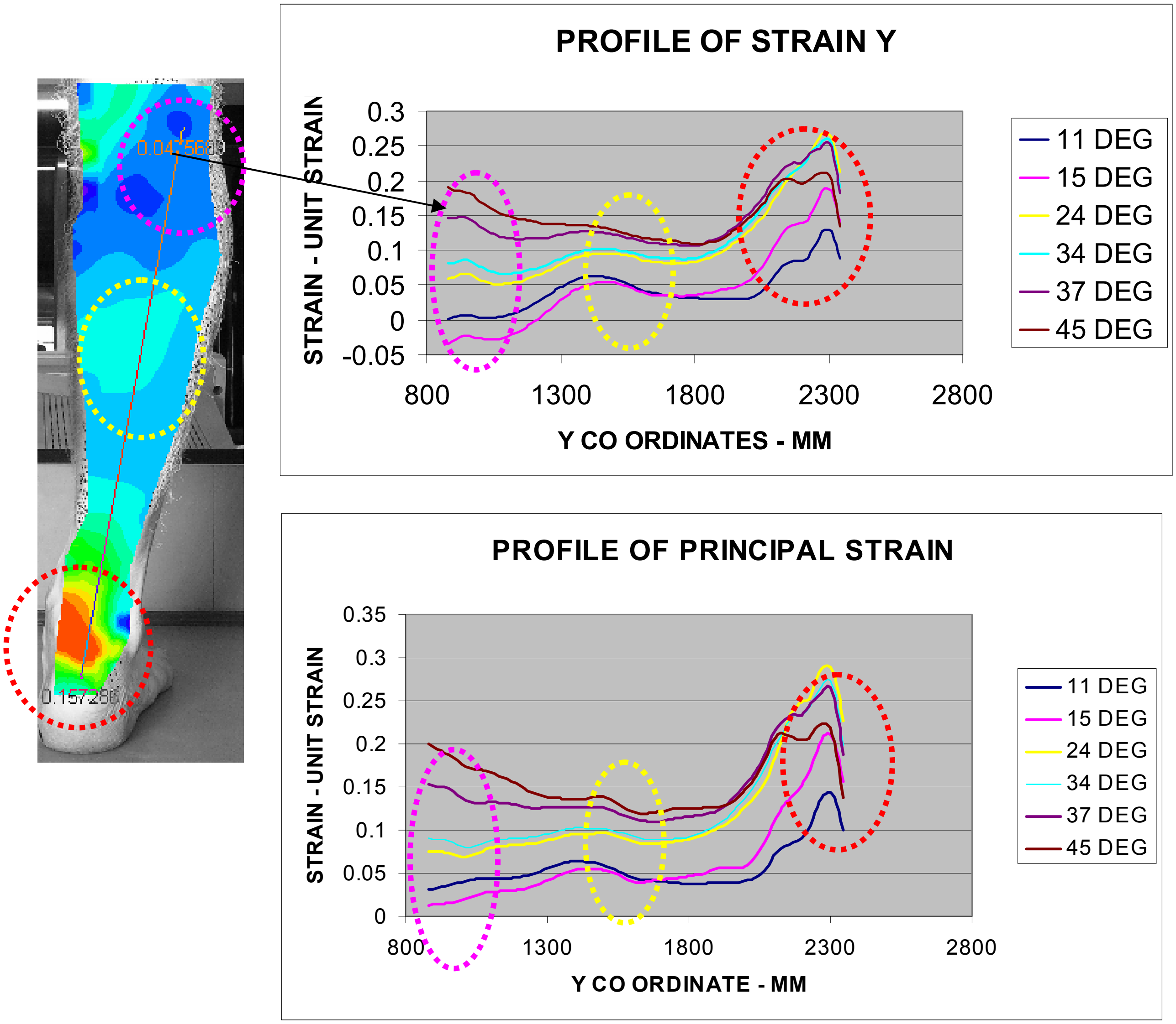


Figure 6-Profiles of Strain Plots

Figure 6 – Graphs indicating the variation of Y-strain and Principal strain 2 (refer figure 4a,b) over the length of the region indicated by the line in **a**. The balloons show the strain variation at the specified key areas of the leg muscles.

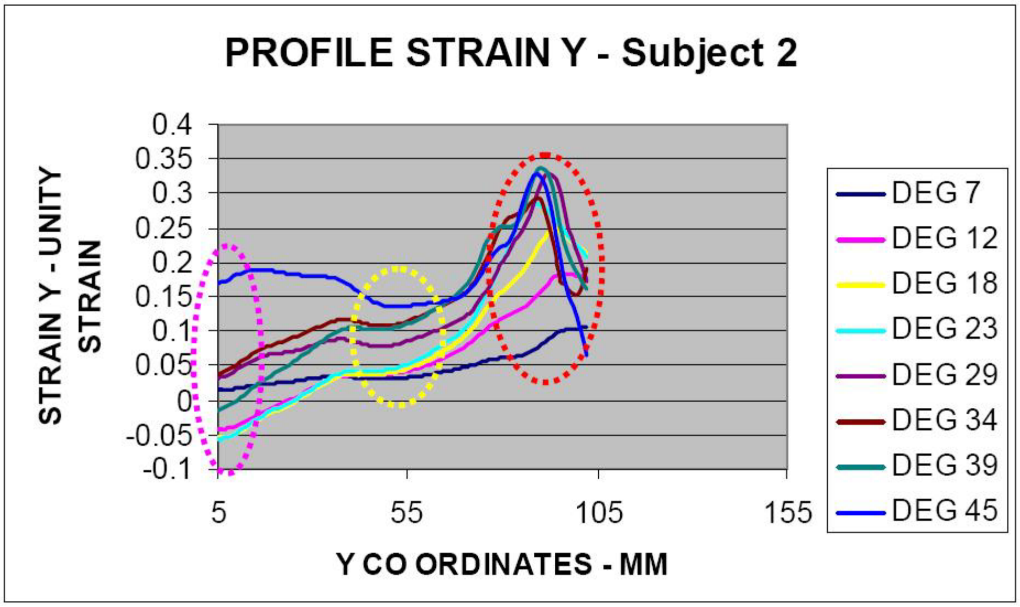


Figure 7 – The Y-Strain variation shown for a different participant. It can be seen that the general trends followed are similar but the dip in strain at the Achilles tendon occurs after 40°. This is an inherent characteristic of the leg of the person undergoing the test.

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