Deformation in the Achilles Tendon when Running with Minimalistic Shoes

Review of Speckle Tracking Algorithm

MATILDA OLSSON
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Hälsenans deformation vid löpning i minimalistiska skor

Analys av speckle tracking-algoritm

Matilda Olsson
June, 2018
Abstract

The main goal of the project was to compare how the Achilles tendon is affected while running with traditional shoes, minimalistic shoes and barefoot. Displacement and strain were calculated both for different shoes and for different foot strike patterns. The calculations were done with a speckle tracking algorithm and displacement was calculated for three different depths in the tendon: deep layer, mid layer and superficial layer.

The goal was also to conduct this analysis after a review of the algorithm used. The review of the algorithm focused on the size of the region of interest, kernel size and frequency. Literature study showed that it is more common to use a smaller kernel size, but the same shape. The region of interest was chosen depending on the size of the tendon. Displacement and strain in the Achilles tendon was calculated for seven subjects and the result did not show any difference in amount of mean deformation due to different shoe types or foot strike patterns.

It was a small sample group but the result indicated a difference in peak displacement between deep and superficial layer depending on different shoe types and foot strike patterns.

The difference in peak displacement between deep and superficial layer was lowest when running barefoot, larger when running with minimalistic shoes and greatest when running with traditional shoes. This result was only achieved when running with rear foot strike pattern. When running with fore foot strike pattern the difference in peak displacement between layers did not change with different conditions.

In all conditions the difference in peak displacement between the layers was greater when running with rear foot strike pattern than when running with front foot strike pattern.

The deep layer displaced more than the superficial layer ($p<0.01$) for all conditions and foot strike patterns.
Sammanfattning

Målet med projektet var att jämföra hur hälsenan påverkas av att springa i olika typer av skor. Barfotalöpning, löpning i minimalistiska skor och löpning i traditionella löparskor tillsammans med påverkan av olika typer av fotisättning inkluderades i studien. Förflyttningen i hälsenan beräknades för tre olika djup.

Ett ytterligare mål med projektet var att genomföra en analys och modifiering av speckle tracking-algoritmen. Analysen av algoritmen genomfördes framförallt med hjälp av en litteraturstudie och val av region, storleken på kärnan och frekvens studerades. Litteraturstudien visade att andra studier har använt mindre kärna men samma form. Storleken på regionen som studerades anpassades efter senans storlek.

Beräkningarna utfördes för sju försökspersoner och inget statistiskt signifikant resultat tydde på att det fanns ett samband mellan medelvärdet på förflyttningen i hälsenan och de olika typerna av skor och fotisättningar.

Resultatet tydde däremot på att det fanns ett samband mellan hur den maximala skillnaden i förflyttning mellan det djupa och det ytliga lagret av hälsenan förändrades beroende på olika skor och fotisättningar.

Den maximala skillnaden i förflyttning mellan det djupa och det ytliga lagret av hälsenan var störst vid löpning i traditionella skor, mindre vid löpning i minimalistiska skor och minst vid barfotalöpning. Det här var resultatet då försökspersonerna satte i hälen först. När försökspersonerna satte i främre delen av foten först uppmättes ingen skillnad mellan de olika skorna.

Vid framfötslöpning var den maximala skillnaden i förflyttning mellan det djupa och det ytliga lagret mindre än vid bakfötslöpning för alla typer av skoförhållanden.

Det djupa lagret av hälsenan förflyttades mer än det ytliga lagret av hälsenan (p<0.01) för alla skoförhållanden och typer av fotisättningar.
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1 Introduction

Minimalistic shoes are a topic of interest for both runners and scientists, mainly since runners want to increase their performance (1). There is an ongoing discussion regarding how minimalistic shoes affect both performance and the risk of injury (2).

Studies agree regarding increased performance and running economy, but the results regarding injuries differ (2). To be able to evaluate the risk of injuries in the Achilles tendon, the tendon had to be investigated during running in the different conditions. Therefore, the aim of this study was to contribute with deeper investigation regarding how the injury risk is affected by different shoe types.

The Achilles tendon is the strongest and thickest tendon in the human body. The Achilles tendon is the connection between the muscle group triceps surae and the bone calcaneus. Triceps surae is responsible for plantarflexion and is also involved in knee flexion. Triceps surae is a large muscle consisting of soleus, lateral gastrocnemius and medial gastrocnemius (3).

It is concluded that the Achilles tendon has a non-uniform behaviour and further knowledge about biomechanical behaviour is needed to be able to evaluate if there is a connection between uniformity and injuries (4). The non-uniform behaviour is believed to be caused by the tendons’ rotational anatomy. Other possible reasons why the Achilles tendon has a non-uniform behaviour is described further in the background chapter.

How displacement, strain and non-uniformity within the Achilles tendon is related to injury risk is not yet concluded. In surgical repaired tendons and elderly tendons the non-uniform behaviour seems to be reduced, this might indicate that a non-uniform tendon is healthier (5).

This study is a part of a larger project where more subjects will be tested and EMG-data will be included in the analysis and contribute to the final result. In this study, the difference in displacement and strain were evaluated in three different conditions: barefoot running, running with minimalistic shoes and running with traditional shoes. The role of foot strike patterns was included in the study. Studies indicate that foot strike pattern affects injury risk and forces applied to the body (2). Some studies state that the injury risk is higher when running with fore foot strike patterns since the forces are higher (6). Other studies state the opposite; Lieberman et al. (7) analysed the collision force and concluded that the forces are greatest for rear foot runners.

The use of automated speckle tracking as a method to analyse tendon is not yet routinely used. Therefore, a part of this project was to determine, how suitable the method is when analysing tendons with help of a literature study. The choice of parameters such as kernel size, region of interest (ROI) and frequency were analysed. The algorithm used in this project is an algorithm developed for estimation of arterial wall strain, and then modified to be able to assess displacement and strain in tendons (5). The algorithm was further modified with help of the findings in the literature study.

Block matching is the most often used speckle tracking method. In the first frame a search area and a kernel are defined. In the next frame the kernel is moved through the search area and the place where the lowest value of the similarity measure calculation is found is where the kernel is assumed to be. The procedure is repeated for all frames and the displacement and strain can be calculated. The algorithm used in this study uses normal cross correlation to calculate the similarity.

Until now, mostly controlled conditions have been studied. This study contributes to knowledge regarding the Achilles tendon’s behaviour while running, which in the current situation is missing. The choice of method was evaluated for further studies.
2 Method and Materials

Seven subjects were included in the study and the right Achilles tendon was analysed for all of
the subjects. The subjects included in the study ran at least 30 km/week and have not had any
injuries in their lower body for the last six months.

Before the trial the subjects filled in a questionnaire including questions regarding how long
the subject had ran at least 30 km/week, if they were fore foot, rear foot or mid foot runners and
when their last injury was.

Subjects with any history of injuries in the Achilles tendon were excluded from the study.
The sample group consisted of both female and male runners in the ages 17 to 38 years.

2.1 Evaluation of the Algorithm

The evaluation of the algorithm was mainly done by literature study. Different studies use different
frequencies, region of interest and kernel size, these parameters were identified. Since studies in this
area are limited, algorithms used for other tendons than the Achilles tendon were also considered,
mainly the patellar tendon.

The three chosen parameters were collected and compared to decide suitable parameters for this
study. Test files were used to evaluate different parameters to be able to detect how the parameters
affected the result and the time consumed for each calculation. At last, the calculations for one
subject was performed with two different kernel sizes and the difference in displacement and strain
was evaluated.

2.2 Trial Setup

During the trials the subjects ran on a treadmill while data was collected with help of ultrasound,
EMG, goniometer and the pedar-system. A 9L linear array transducer (GE Healthcare) with 10
MHz frequency connected to a Vivid-q ultrasound machine was attached to a custom-made holder
at the middle of the right Achilles tendon.

The conditions analysed were running with traditional shoes, minimalistic shoes and barefoot.
The subjects started with a warm up of 10 minutes followed by running at 12 km/h, walking at
3 km/h and 5.5 km/h for 15 seconds each. The running was performed with fore foot strike, rear
foot strike and habitually foot strike pattern. This was repeated two times for all of the three
conditions. In total 30 ultrasound files was collected for each subject. The trial was done in
randomized order for each subject.

Achilles tendon displacement and strain were calculated for the different conditions using au-
tomated speckle tracking. The algorithm used is designed to make it possible to calculate the
displacement at three different depths.

2.3 Speckle Tracking

The first and last frame for each step was identified with help of the pedar-system. The pedar-
system measures the interaction between the foot and ground. The pedar files were implemented
in MATLAB (R2016a, MathWorks Inc., Natick, MA, USA) and the time for each heel insertion
was given with help of an existing algorithm.

To calculate the frame number the sync time was needed. The sync time is the time difference
between when the ultrasound start collecting data and when the pedar-system starts collecting
data. Sync time is given for each file when opened in EchoPAC. The heel insertion time and sync
time together with the frame rate gives the frame numbers for each step.

The ultrasound files were converted to hdl-files with EchoPAC and then imported to MATLAB.

The in-house block-matching speckle tracking algorithm was used to assay displacement and
strain in the Achilles tendon. The algorithm was implemented in MATLAB and applied on the
B-mode ultrasound data. Start and end frame for each step were entered manually.

2D motion estimation was performed using a kernel size of $52\lambda \times 25\lambda$, 80% kernel overlap, and
normalized cross correlation as similarity measure. For one subject the calculations were performed
both with a kernel size of $52\lambda \times 25\lambda$ and a kernel size of $32\lambda \times 15\lambda$. 
Region of interest was placed manually and the size differed for each subject, depending on the thickness of the Achilles tendon. ROI was larger for displacement calculations than for strain calculations. The ROI for displacement calculation was approximately 40 mm x 10 mm. The width when calculating strain was constant at 25 mm and the length varied between 1.8 mm and 2.4 mm. Figure 1 shows how the image is visualised for the user and how region of interest is placed in the middle of the tendon.

![Ultrasound image and Region of interest](image)

*Figure 1: Printscreen of the ultrasound image for one subject*

Five steps for each condition were analysed and mean values within and between subjects were calculated.

Resulting displacement and strain curves and values for each step were saved in Excel (2016, version 15.33) and MATLAB.

Mean and median peak displacement and strain curves for the three different conditions and the different foot strike patterns was calculated and plotted in MATLAB. Displacement and strain for the different conditions was also plotted within each type of foot strike pattern. Therefore, twelve plots per subjects were plotted and analysed. This procedure was repeated for difference in displacement between the different layers.

### 2.4 Statistical Analysis

Mean values were calculated in MATLAB and repeated ANOVA measures were performed. Repeated measures ANOVA is an extension of dependent t-test and is also called within-subjects ANOVA. The test detects differences between related means.

The null hypothesis states that the means for all of the conditions are equal and the alternative hypothesis states that at least one mean is significantly different. The test does not give information about where the difference occurs, only if there is a significantly difference or not.

Repeated measures ANOVA is more powerful than independent ANOVA since it removes the variability due to individual differences between subjects.

Repeated ANOVA was performed both to calculate difference between conditions, foot strike patterns and difference in displacement between the superficial and deep parts for the different conditions. P-values lower than 0.01 was considered statistically significant.
3 Results

3.1 Algorithm

The algorithm, originally made for cardiac tissue, was further adapted to tendons. Unnecessary loops and ECG calculations were removed or changed which reduced the calculation time.

Table 1 is an overview of the results from the literature study.

<table>
<thead>
<tr>
<th>Article</th>
<th>Kernel size [mm]</th>
<th>ROI [mm]</th>
<th>Tendon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>3.26x1.63</td>
<td>Adapted</td>
<td>Patellar, gastrocnemius</td>
</tr>
<tr>
<td>4</td>
<td>4.3x2.2</td>
<td>8.6x3.9</td>
<td>Porcine flexor</td>
</tr>
<tr>
<td>5</td>
<td>5.72x2.75</td>
<td>20</td>
<td>Achilles</td>
</tr>
<tr>
<td>6</td>
<td>6.8x3.4</td>
<td>13.4x6.03</td>
<td>Flexor digitorum superficialis</td>
</tr>
<tr>
<td>7</td>
<td>0.56x0.56</td>
<td>2.1x0.56</td>
<td>Flexor digitorum superficialis</td>
</tr>
<tr>
<td>8</td>
<td>1x0.4</td>
<td>9.8x3</td>
<td>Achilles</td>
</tr>
<tr>
<td>9</td>
<td>2x1</td>
<td>15x3</td>
<td>Achilles</td>
</tr>
<tr>
<td>10</td>
<td>2x0.8</td>
<td>26x4</td>
<td>Porcine flexor</td>
</tr>
</tbody>
</table>

The average kernel size found in literature was 3.2 mm x 1.6 mm. The time it took for each calculation with kernel sizes from 2 mm up to 8 mm did not differ more than a few seconds.

Region of interest and kernel size was decided to be kept as initial. The shape of the kernel size was rectangular with a width of two times the length.

For the subject investigated with two different kernel sizes the peak difference in displacement between the layers differed. The peak displacement values were lower with a smaller kernel size (32λ x 15λ), but the difference between the conditions and foot strike patterns were the same.

3.2 Deformation in the Achilles Tendon

For all subjects the deep layer was displaced the most, then middle layer and lastly the superficial layer. This was the case for all conditions and foot strike patterns. Repeated measures ANOVA resulted in p<0.01 in all cases which was considered statistically significant.

The result in this study does not indicate that there is a difference in amount of mean displacement in the tendon linked to which shoe type the subject were running with. It did not show that the mean displacement is either larger or smaller depending on foot strike pattern. This was the case for all kind of deformation, both displacement and strain.

For some of the subjects the mean displacement and strain was larger when running with traditional shoes and for some subjects the mean displacement and strain was larger when running with minimalistic shoes or barefoot. For some of the subjects the plots of mean displacement showed similar results but for some subjects the plots differed. An example of how the mean displacement differed between subjects is shown in Figure 2 below.

Since the mean deformation differed for each subject it did not lead to any statistically significant result. This was the case both between different shoe types and foot strike patterns.

However, the result indicated that the uniformity of the tendon differed for different shoe types and foot strike patterns. The uniformity is in this case defined as the difference between displacement in the deep layer and the displacement in the superficial layer. There was a statistically significant difference between the displacement in the different layers for all shoe types and foot strike patterns.

The difference in peak displacement between the deep and the superficial layer was greater when running with traditional shoes than when running with minimalistic shoes. Difference in peak displacement between the layers was lowest when running barefoot.

Mean and median peak difference values for all conditions is shown in Table 2 below. In Table 2 it can be seen that both mean and median peak difference between the layers were larger when running with traditional shoes, then minimalistic shoes and lowest for barefoot running.
Figure 2: Mean displacement for subject 2 and 7 with rear foot strike pattern

Table 2: Mean and median peak displacement ± SD in different layers when running with rear foot strike pattern and with different shoe types.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Deep disp. [mm]</th>
<th>Superfic. disp. [mm]</th>
<th>Δ disp. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barefoot, mean</td>
<td>2.2 ± 0.7</td>
<td>0.8 ± 0.2</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>Barefoot, median</td>
<td>2.2 ± 0.7</td>
<td>0.9 ± 0.3</td>
<td>1.3 ± 0.8</td>
</tr>
<tr>
<td>Minimalistic, mean</td>
<td>2.3 ± 0.5</td>
<td>0.7 ± 0.4</td>
<td>1.6 ± 0.5</td>
</tr>
<tr>
<td>Minimalistic, median</td>
<td>2.3 ± 0.5</td>
<td>0.6 ± 0.5</td>
<td>1.7 ± 0.5</td>
</tr>
<tr>
<td>Traditional, mean</td>
<td>2.4 ± 0.4</td>
<td>0.7 ± 0.3</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td>Traditional, median</td>
<td>2.6 ± 0.5</td>
<td>0.7 ± 0.3</td>
<td>1.9 ± 0.3</td>
</tr>
</tbody>
</table>

In Table 3 the differences in displacement between the layers when running with different foot strike patterns and shoe types are presented. As can be seen in Table 3 there was a larger difference between the deep and superficial layer when running with rear foot strike patterns than when running with fore foot strike pattern. This was the case for all shoe types. It can also be seen that the difference between shoe types presented in Table 2 is only accurate for rear foot strike pattern and not front foot strike pattern.
Table 3: Overview of mean peak differences ± SD in different layers when running with different shoe types and foot strike patterns.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Deep disp. [mm]</th>
<th>Superfic. disp. [mm]</th>
<th>Δ disp. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barefoot, front</td>
<td>2.0 ± 0.7</td>
<td>0.7 ± 0.3</td>
<td>1.3 ± 0.7</td>
</tr>
<tr>
<td>Barefoot, rear</td>
<td>2.2 ± 0.7</td>
<td>0.8 ± 0.2</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>Minimalistic, front</td>
<td>1.9 ± 0.7</td>
<td>0.6 ± 0.4</td>
<td>1.3 ± 0.6</td>
</tr>
<tr>
<td>Minimalistic, rear</td>
<td>2.3 ± 0.5</td>
<td>0.7 ± 0.4</td>
<td>1.6 ± 0.5</td>
</tr>
<tr>
<td>Traditional, front</td>
<td>2.1 ± 0.6</td>
<td>0.8 ± 0.5</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>Traditional, rear</td>
<td>2.4 ± 0.4</td>
<td>0.7 ± 0.3</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td><strong>Total, front</strong></td>
<td><strong>2.0 ± 0.6</strong></td>
<td><strong>0.7 ± 0.4</strong></td>
<td><strong>1.3 ± 0.5</strong></td>
</tr>
<tr>
<td><strong>Total, rear</strong></td>
<td><strong>2.3 ± 0.6</strong></td>
<td><strong>0.7 ± 0.3</strong></td>
<td><strong>1.6 ± 0.6</strong></td>
</tr>
</tbody>
</table>

When running with front foot strike pattern the difference in displacement between the layers were 1.3 mm for all shoe types. When calculating the mean peak displacement and including all foot strike patterns, the difference between the layers were 1.4±0.4 mm for both barefoot running and running with minimalistic shoes. The mean peak displacement when running in traditional shoes were 1.6±0.5 mm.
Discussion

This study found smaller values of displacement in the Achilles tendon than earlier studies. This could be because of the trial set up, which in this case was different from other studies. There is at least one study with displacement values in the same size as this study (4). Previous studies have concluded underestimation of the displacement and it has been predicted that active conditions might lead to more uniform behaviour than passive conditions (16), (2). This might be some of the reasons for the small values of displacement.

The plots within each subject did show a trend that the mean displacement was larger when running with traditional shoes but not for all subjects. No statistically significant result was achieved since the sample group was small and there were differences between the subjects. It might still be interesting to investigate amount of mean displacement further with a larger sample group since a trend was detected.

Since the mean amount of displacement and strain did not show any statistically significant result the uniformity within the tendon was further investigated. To be able to exclude differences due to foot strike pattern, rear foot running was calculated and plotted in the different conditions. The result showed most uniform behaviour when running barefoot and most non-uniform behaviour when running with traditional shoes. Minimalistic shoes seemed to have less uniform behaviour than when running barefoot but more uniform behaviour than running with traditional shoes.

Both median and mean values were calculated and they indicated the same result. All of the conditions and foot strike pattern resulted in a non-uniform tendon but the amount of non-uniformity might differ.

The algorithm only calculated strain for the mean displacement and not for each layer. Therefore, strain is not further evaluated in this study. This has now been added in the algorithm. Since Boagaerts et al. (4) found differences in strain in the different layers this can be interesting to study in the future with the developed algorithm.

Achilles injuries increase by age, and studies show that the tendons are more uniform in middle-age adults than younger adults. Uniformity might happen since gliding between tendon fascicles is reduced. Slane et al. (13) states that a more uniform tendon affects both plantarflexor performance and the injury risk. If this is the case, it would be interesting to see if Achilles tendon injuries increase when running with minimalistic shoes since tendon seem to behave more uniform.

As mentioned earlier the Achilles tendon has a rotational anatomy which probably is the reason for the non-uniform behaviour. The deep layer of the tendon is attached to lateral gastrocnemius and the superficial layer is attached to medial gastrocnemius. Since the different layers of the tendon is attached to different muscle tendons the result of this study in association with the result of the EMG-data might give information about if the different muscles are more or less activated during different conditions. The non-uniformity might enable the muscles to act more independently (15).

The Achilles tendon behaved more uniform when running with fore foot strike pattern than rear foot strike pattern for all conditions. This is the first study found where the deformation in the Achilles tendon is calculated when running with different foot strike patterns. Earlier studies have analysed the forces applied to the body when running with different foot strike patterns. The study results differ; some studies state that it can not be concluded if the impact forces affect the risk of injuries (17), others state that the impact forces are highest for rear foot runners (18), (7).

At least two studies study the Achilles tendon force and they both conclude that the Achilles tendon force is highest when running with fore foot strike pattern (19), (6).

After reviewing earlier studies the most common result is that the impact force, the force applied in the beginning of the stance, is lower when running with front foot strike pattern but the forces applied to the Achilles tendon is higher. One study states that the patellofemoral tendon force is lowest when running with front foot strike pattern which may indicate that front foot strike pattern is better for knees but worse for the ankle with respect to injury risk (19).

Some studies state that runners tend to change to front foot strike pattern when running with minimalistic shoes (2), therefore it would be interesting to analyse with the pedar-system, if habitually running is changed with shoe type. This study is most likely during too short time to change foot strike pattern, but if the study design is changed in the future it would be interesting (18).
The difference in displacement due to shoe types does only seem to be accurate when running with rear foot strike pattern. This might indicate that traditional shoes are designed for rear foot runners (7). For runners who are fore foot runners the deformation in the Achilles tendon is not affected when changing shoes.

Regarding the algorithm, some modifications made the calculations faster, when this was achieved focus was on evaluating different parameters. To continue to develop the method and the algorithms used it would be beneficial to introduce a standard way to present the parameters used in studies. This will improve the possibility to review and develop algorithms further.

The kernel size in this study was the biggest one found. Larger kernel size is more accurate but takes more computational load. A too big kernel size however leads to good match every time. Because of this the optimal size needs to be found.

The kernel size used in this study was chosen with help of comparing displacement from speckle tracking with displacement using manual tracking (5).

Changing the kernel size did not affect the time substantially, therefore it is the accuracy of the calculations that should decide the size.

A smaller kernel size resulted in lower peak displacement compared to the original kernel size. But it gave the same total result since the relationship between the different conditions and foot strike patterns were the same.

The spatial resolution was lower in lateral direction than in axial direction. The displacement calculations in this study was made in lateral direction and therefore dependent of the lateral resolution. To compensate for the lower resolution in lateral direction the kernel size was larger in lateral direction than in axial direction but the calculations are most likely less accurate in lateral direction than in axial direction due to poorer resolution.

4.1 Limitations

The main limitation in this study was the small sample group. Since this thesis is a part of a larger project more subjects will be included for the final result.

Another limitation is the fact that the subjects only participated in the study once. Two data collections were done for each condition and subject, but to get more reliable result it would be advantageous to repeat the trial at least two times.

A part of this study was to evaluate the already existing algorithm. This could not be optimally done since the access to true displacement and strain was missing. Therefore, it was only the kernel size that was evaluated with measurement and the evaluation of the whole algorithm was mainly done with help of a literature study.

This study was not blinded, the one who performed the calculations knew which file corresponded to which condition.

Only one location of the tendon was investigated and the location might have altered between the subjects, which might have been another possible limitation.

4.2 Future Work

As mentioned in the background chapter, the use of higher frequency ultrasound allows tracking of smaller structures which might be useful when tracking tendons (4). This study showed displacements of less than two millimeters, therefore, higher frequency would be preferable. Higher frame rate will limit problems with out-of-plane motion. Using higher frequency and frame rate might lead to more accurate result.

In future work, it would be interesting to analyse forces and angles, this can be done if the subjects for example runs on a force-measuring treadmill. Forces are mainly interesting to be able to investigate the effect of foot strike patterns further. In this trial setup, a goniometer was used but the result was not included in this thesis.

Since results from long term studies are missing it would be interesting to do one data collection at one point and then let the subject run in minimalistic shoes for six months and then repeat the data collection to be able to compare the results and exclude influence of being unfamiliar with running in minimalistic shoes.
5 Conclusion

First of all, it can be concluded that automated speckle tracking to measure deformation in tendon is a suitable and effective method but it can be further developed.

To measure and compare difference between different layers in the tendon seems to be a suitable method to evaluate the effect of different conditions, such as shoe types or foot strike patterns.

The displacements in this study were smaller than in earlier studies and the differences between the conditions were too small to be able to draw any conclusion regarding the effect of running with different shoes and foot strike patterns.

The main conclusion to be drawn is that a larger sample group is needed to be able to generate statistical significant results both regarding the used method and deformation within the tendon caused by running with different shoe types and with different foot strike patterns.
A State of Art

A.1 Achilles Tendon

In this project, the Achilles tendon has been studied. The data collection was done when running in traditional shoes, minimalistic shoes and barefoot. To be able to analyse the result and compare the risk of injury, knowledge about the Achilles tendon is necessary.

A.1.1 Anatomy and Function

The Achilles tendon is the strongest and thickest tendon in the human body (20). The structure consists of collagen triple helices, fibrils, fibres and fascicles. The fascicles are structured with a rotation from proximal to distal, which gives the tendon a twisted anatomy (4). The direction of the force applied to the tendon is the main factor to determine the orientation of the collagen fibres.

The Achilles tendon is the connection between the muscle group triceps surae and the bone calcaneus, as seen in Figure 3a. Triceps surae consists of lateral gastrocnemius, medial gastrocnemius and soleus. Gastrocnemius is more posterior and soleus is anterior. Both muscles are responsible for plantarflexion and gastrocnemius is also involved in knee flexion. Plantarflexion can be described as pointing the toes down, as shown in Figure 3b.

![Muscles, tendon and bone.](image1)

![Dorsi- and plantarflexion.](image2)

*Figure 3: Muscles responsible for plantarflexion (adapted from(3)).*

The Achilles tendon has many functions, apart from transmitting force between muscle and bone, it also stores and releases energy, protects the muscle from stretch damage and enhances muscle performance (4).

A.1.2 Strain, Displacement and Deformation

Displacement can be defined as the actual change of tendon length in meters. Strain is defined as elongation divided by resting length of the tendon and is given in percent. In other words, strain is the relative displacement. Deformation is caused by body forces and external loads.

Speckle tracking as a method to determine strain and displacement will be evaluated in section A.3.2.

A.1.3 Deformation within the Achilles Tendon

Several studies have shown a non-uniform displacement within the Achilles tendon, both in passive elongation and in voluntary isometric contraction (4). This non-uniform behaviour has been observed when studying three different layers in the tendon. The superficial layer, the middle layer and the deep layer (21).

The uniformity has been studied both with high frequency ultrasound and conventional central frequency of 10 MHz and the common used block matching method. Both of the studies mentioned,
concluded that there is a greater displacement in the deeper layer than in the middle layer and a
greater displacement in the middle layer than in the superficial layer (4), (21).

Some studies also measured the strain within the different layers. Measure of regional strain is
challenging, but it was concluded that the highest regional strain is in the superficial layer. The
result was only significant in passive elongation and not in voluntary isometric elongation (4).

It has been discussed why the Achilles tendon has a non-uniform behaviour. Some of the
possible explanations are that it occurs because of the tendons rotational anatomy. It has been
shown, that in the patellar tendon, there are local material differences affecting the behaviour,
which may also be accurate in the Achilles tendon.

At the insertional level of the Achilles tendon, the superficial fibres relate mostly to the gas-
trocnemius medialis subtendon and the deep fibres mostly relate to the gastrocnemius lateralis
subtendon which might also be a reason for the non-uniform behaviour (4).

Another possible explanation to the fact that the displacement is greatest where the strain is
the smallest might be because the deep layer of the Achilles tendon twists the most. The twisting
might lead to higher pre-tension and therefore less extra straining and more displacement occur at
this place (4).

How displacement, strain and non-uniformity within the Achilles tendon is related to injury
risk is not yet concluded. A qualified guess is though, that a non-uniform behaviour of the Achilles
tendon is preferable. This since it has been reported that after surgical repair the tendon acts
more uniform than a uninjured tendon (5). Younger adults have a less uniform Achilles tendon
than older adults. This in association with the fact that after surgical repair there is a decrease in
performance indicates that a non-uniform Achilles tendon is beneficial.

A.2 Minimalistic Shoes

Minimalistic shoes are a topic of interest for both runners and scientists (1). A minimalistic shoe
is a shoe without cushioning. The minimalistic and traditional shoes used in this study are shown
in Figure 4. There is an ongoing discussion regarding how minimalistic shoes affect performance
and the risk of injury (2). Therefore, many studies within the area has been done and are still
ongoing.

(a) Traditional shoes. (b) Minimalistic shoes.

Figure 4: The two different shoes used in this study.

A.2.1 Foot Strike Patterns

There are mainly three different foot strike patterns for runners. Fore foot strike, mid foot strike
and rear foot strike. A fore foot strike means a more plantar flexed foot at landing and rear foot
strike means a dorsi flexed foot at the landing, see Figure 3b. Foot strike pattern is of interest in
this study since it is believed that foot strike patterns affect injury risk and forces applied to the
body. Some studies also suggest that running with minimalistic shoes might affect the runners’
foot strike pattern (2).

Different opinions regarding how different foot strike patterns and shoe types affect forces
applied to the body exist. In a study from 2016 by Hashizume and Yanagiya (6), different forces
and moment arms were calculated for the different foot strike patterns. The result was that both
the Achilles tendon force and joint reaction force were greatest for the fore foot strike followed by the mid foot strike and then rear foot strike. The same goes for the ground reaction force and moment arm. The Achilles tendon moment arm on the other hand was the same for all foot strike patterns. The authors state that large Achilles tendon force leads to overuse injuries as tendinopathy in the Achilles tendon. Therefore, it was concluded that running related injuries are greater in fore foot strikes than rear foot strikes. These results were achieved both with forward dynamics and inverse dynamics (6).

In opposite to this study, Lieberman et al. (7) state that habitually barefoot endurance runners often run with fore foot strike, sometimes mid foot strike, less often rear-foot strike and runners habitually running with traditional shoes run with rear foot strike. Kinematic and kinetic analyses showed that even on hard surfaces, barefoot runners who fore foot strike generate smaller collision forces than rear foot strikers running with traditional shoes. In Figure 5 the result from one of the runners can be seen. As mentioned before, fore foot strike imply a more plantar flexed foot at landing which can decrease the effective mass of the body that collides with the ground (7).

![Figure 5: Vertical ground reaction force for three different strike patterns.](image)

a) Rear foot strike barefoot, b) Rear foot strike traditional shoes, c) Fore foot strike barefoot (7).

Some studies indicate that people running in minimalistic shoes with rear foot strike pattern experience a greater vertical loading rate than those who run with other strike patterns (18). Because of these findings it was of interest to study both fore foot, rear foot and habitual running in this study.

Several studies argue that high impact forces while running are part of the reason for injuries, but other authors also argue that chronic low impact forces will weaken the bones and supporting structures and that structures will adapt to high impact forces if they have sufficient rest periods between running (22).

Lastly it should be mentioned that Nigg states ”one cannot conclude that impact forces are important factors in the development of chronic and/or acute running related injuries” (17).

To conclude, more studies are needed within this area to be able to draw an accurate conclusion. Particularly long term studies are needed.
A.2.2 Performance and Injuries

Opinions regarding how minimalistic shoes affect runners’ performance and primarily its effect on injury risk differ.

Performance has been studied in many short-term studies and at least one long-term study has been done. The results indicated that running with minimalistic shoes increased performance, in terms of increased five km trial performance and running economy. Running at higher speeds implied the highest increase in performance. This might indicate that minimalistic shoes is better suited for elite runners that maintain high speed (2).

At the moment, there are no long-term study results on how minimalistic shoes affect the injury risk, but there are ongoing studies (2). As mentioned before, results regarding short-term effect on injury risk is divided. Fuller et al. (2) state that there are some evidence indicating that minimalistic shoes increase injury risk. In a later and longer lasting study, Fuller et al. (19) state that the runners experience a greater pain when running in minimalistic shoes than traditional shoes, if running more than 35 km/week. A relationship between body mass and pain is also found, runners with higher body mass experienced greater pain when running in minimalistic shoes (19).

Cohler and Casey (23) conducted a survey, which 566 members of the Chicago Area Runner’s Association filled in. The main result indicated that running with minimalistic shoes made knee pain better but foot pain worse (23). Of course, one should note that this is a descriptive study which indicates that further research within this area must be done to be able to draw any conclusion.

A.3 Speckle Tracking

Automated speckle tracking as a method to analyse ultrasound images is widely used. The method has been mainly applied to cardiac tissue and blood vessels and tendon has not been as routinely analysed with this method.

Block matching is the most often used speckle tracking method. In the first frame a search area and a kernel is defined. In the next frame the kernel is moved through the search area and the place where the lowest value of the similarity measure calculation is found is where the kernel is assumed to be. The procedure is repeated for all frames and the displacement can be calculated.

With automated speckle tracking it is possible to save time, reduce the user-dependence, and there is no need for known landmark which is required when using manual methods (8).

A.3.1 Algorithm

Speckle tracking with help of block matching is a non-invasive method that measures similarity for every kernel inside the chosen search area. There are different techniques to measure similarity, one technique is sum of absolute difference. The lowest sum of absolute difference then indicates the best agreement and is assumed to be the position of the kernel after moving.

Many studies within this area has been done, some use in house made algorithms and some use commercial ultrasound speckle tracking algorithms. It can be concluded that the results differ between the studies.

Speckle tracking can be done both directly on radio frequency (RF) data and on brightness mode (B-mode) images. RF-data includes more information and is not affected by the post-processing steps. It does though require large storage space and larger computational load (24). In line with this, Slane and Thelen (25) state that tracking is improved when using RF-data instead of B-mode data. Despite this, B-mode is most often used since it requires less computational load.

In this study, apart from the actual algorithms, choice of frequency, transducer, size of the search field, kernel size and the shape of the kernel size and region of interest (ROI) will be studied.

The algorithm used in this study has been evaluated by Fröberg et al. (16) and it has the kernel size $52\lambda \times 25\lambda$ where $\lambda$ is the wavelength transmitted from the ultrasound. The ROI is placed manually and has the width 25 mm and the length is adjusted to be the same as the thickness of the subjects’ Achilles tendon. The algorithm uses 80 % kernel overlap, which mean the kernel is moved 20 % of its size before each new similarity calculation. Overlapping kernels have been
used in other studies with good results since it increases tracking accuracy under the assumption of limited deformation (16).

The study by Fröberg et al. (16) indicated that speckle tracking systematically underestimates the displacement in the Achilles tendon. The underestimation was relatively constant and a likely explanation was assumed to be out of plane motion causing tracking to fail momentarily. This is not the only study indicating underestimation of the displacement (16).

As mentioned, different techniques can be used to calculate the match between different frames. The three most frequently used methods are normalized cross-correlation (NCC), sum of squared difference (SSD) and sum of absolute difference (SAD). All the techniques show good result and small differences in performance, but there are advantages and disadvantages with the different methods. The advantage with NCC is that it compensates for mean and standard deviations, but it requires higher computational load. The greatest advantage with SAD is its low computational load which makes it more suitable for real-time use. With SSD larger mismatches are more heavily weighted than small mismatches (12), (10). The technique should be chosen with regards to their advantages and disadvantages to suit the current conditions. The algorithm used in this study calculates the normalized cross-correlation. Choice of technique is of interest in this study since it might affect the efficiency of the algorithm.

Interpolation can be done either on the kernel and search region or on the matrix after the similarity measure. Interpolation of the matrix after similarity measure is more efficient and widely adapted (10).

Many studies indicate that automated speckle tracking is a promising method to estimate displacement and strain in tendons. It is also shown that with automated speckle tracking it is possible to track larger displacement than with anatomic landmarks (8), (9), (10).

When reviewing the effectiveness of the algorithms the choice of kernel size was studied since it is one of the trade-offs that should be done. Large kernel size may cause ambiguous matches and is computationally intensive and with small kernel size large tendon displacement between the frames may not be captured which can cause mismatching (12).

A.3.2 Limitations

Out of plane motion is the largest limitation within speckle tracking in tendons. Earlier studies show good results in the accuracy of displacement data but the results regarding strain data is varied. Strain requires tracking of difference in displacements within a region which makes it more challenging (16).

Regarding commercial available algorithms, the results also differ. Some studies state that neither displacement nor strain can be measured accurately with the commercial available algorithms, but some studies state that displacement can be measured accurately (10). Results regarding strain estimations with commercial algorithms is more consistent. It has been concluded that commercial available algorithms such as EchoPAC 110.1.2, 2D strain (GE Healthcare) do not show accurate result in strain estimation (16). Therefore, an in house developed algorithm was used in this study.

In available studies using speckle tracking to measure tendon deformation, the method has been to study passive and active elongation. Some studies have used ultrasound during walking on a treadmill, but no studies, using the same method, with a subject that runs on a treadmill have been found. Some predict that active conditions might lead to more uniform behaviour than passive conditions (4).

The greatest trade off, using automated speckle tracking, is between efficiency and accuracy.

A.4 Latest Techniques

One method to improve the accuracy of speckle tracking in tendons is suggested to be the use of high frequency ultrasound. This has mainly been applied in Leuven, Belgien (4). High frequency enables tracking speckle of smaller structures. Conventional ultrasound frequency is around 10 MHz and in one study 21 MHz has been used. Striated speckle pattern measured with 10 MHz has an average width of 0.3 mm and with 21 MHz the average width is 0.14 mm. These values indicate that it is possible to image large fascicles with 10 MHz and with 21 MHz it is possible to image tendon fibres (4).
With high frequency, there is a higher resolution along the beam propagation direction but it also implies a reduction of the field of view along the lateral direction. This is the main trade off when using high frequency ultrasound.

As mentioned earlier, out of plane motion, is a motion that needs to be considered to achieve more accurate results from speckle tracking in tendons. To overcome this limitation when measuring strain, 3D ultrasound has been used. Acquisition of 2D-high frequency ultrasound images have been combined with a mechanical guided system. The study showed that 3D strain estimation is more accurate than 2D, but acquisition of appropriate 3D ultrasound images remains a challenge (26).

It was concluded that the technique is a good alternative to estimate 3D tendon strain when using high-frequency transducer. To improve the method, the author suggest to investigate the 3D ultrasound image reconstruction strategy along the elevation direction. To reduce errors related to the increased friction and uneven step size of the motor, information about the movement of the probe should be included in the image reconstructing process (26). The motor is the device that was used to displace the ultrasound transducer during the trial.

Of course, it must be taken into account that this is just one study and more studies have to be done to be able to conclude something.

Combination of block matching and optical flow has also been studied. With help of optical flow, displacement is calculated and the frame intervals are selected, then block matching is done. To reduce errors, the displacement on frames in between is interpolated with help of the optical flow results. The study showed significantly more accurate tracking results when adaptable determining the frame interval. This method does only work for small amount of motion and not for too large target motion (27).

In the future, another application for automated speckle tracking might be to analyse the collateral ligament strain in the knee. Today there is limited knowledge about the ligaments. Therefore, a method able to provide information about the ligaments will be interesting.

At least one study has studied this application, but faced some challenges (28). Some challenges were related to the limitations of using a 2D imaging modality to characterise 3D motion and other challenges were specific to this application. To be able to investigate the application further, earlier mentioned techniques, such as high frequency ultrasound and 3D imaging need to be applied.

To sum up, more studies are needed to be able to continue to improve speckle tracking, where high frequency ultrasound seem to be a promising technique (4).
References


