GAIT ANALYSIS BY MULTI VIDEO SEQUENCE ANALYSIS

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ABSTRACT

The project presented in this article aims to develop software so that close-range photogrammetry with sufficient accuracy can be used to point out the most frequent foot malpositions and monitor the effect of the traditional treatment. The project is carried out as a cooperation between the Orthopaedic Surgery in Northern Jutland and the Laboratory for Geoinformatics, Aalborg University. The superior requirements on the system are that it shall be without heavy expenses, be easy to install and easy to operate. A first version of the system is designed to measure the navicula height and the calcaneus angle during gait. In the introductory phase of the project the task has been to select, purchase and draw up hardware, select and purchase software concerning video streaming and to develop special software concerning automated registration of the position of the foot during gait by Multi Video Sequence Analysis (MVSA). Results show that the developed MVSA system, in the following called Fodex, can measure the navicula height with a precision of 0.5-0.8 mm. The calcaneus angle can be measured with a precision of 0.8-1.5 degrees.

1. INTRODUCTION

The foot is the foundation of the body, and well-functioning feet are a condition of unproblematic performance of walk, running and load of the motor apparatus. It is well known that even insignificant malpositions, especially claw foot and flatfoot, and malfunctions, especially drop of the metatarsal arch or the longitudinal arch, may cause overloading and attrition in the very foot and the rest of the motor apparatus. Pain in the motor apparatus occurs very often and often demands a notification of illness. This is in Denmark the most frequent cause of early retirement. The methods used so far to demonstrate malposition (clinical examination and soleprint) can only show severe cases. The mal positions which are most often the cause of malload injuries, are claw foot and drop of the longitudinal arch of the foot under load (functional hyperpronation). A characteristic of claw foot is a high foot arch and inward angling of the heel (calcaneo varus). A characteristic of the hyperpronated foot is that the longitudinal arch of the foot drops down very much under load with concurrent exaggerated outward angling of the heel (calcaneo valgus). The height of the foot arch is traditionally estimated through the height of the crest of the navicula bone (tuberositas ossis naviculare) from the floor, and the drop under load is indicated as the height difference between loaded and unloaded position, also called the navicular drop. The misangling in the heel is indicated as the angle at maximum loading, also called maximum calcaneus angle.

In common clinical practice the navicula drop and the navicula angle are usually measured with a ruler and a hand-held angle meter. Ordinary video recording from behind at gait and running on a treadmill is used at a qualitative assessment of the walking and running style, but cannot give detailed information about the position and function of the foot. In a scientific context the foot
position can be analyzed by a 3D gait analysis in laboratories, in which a number of cameras are used simultaneously.

In the last decades several different motion capture systems have been used in the clinical setting (Woodburn 2004), (Rattanaprasert 1999), (Theologis 2003) and as an experimental setup (Areblad, 1990), (Hunt 2001), (Carson 2001), (Simon 2006), (Leardini 2007).

Motion capture systems from Vicon, Qualisys and other so-called state of the art systems are in clinical medicine and biomechanics research used to analyze different motions of the human body. These systems are normally based on images from 6-8 cameras (or more). The systems track active or passive markers attached directly to the skin or to a special suit. The markers are placed according to a specific scheme depending on what kind of motion that is to be analyzed. Before the motions can be analyzed each marker must be identified initially by a semi-automated procedure.

The system presented in this project is designed only to capture motions of the foot during gait performed on a treadmill. This makes it possible to reduce the number of cameras compared to the above-mentioned systems. The system tracks specific anatomical landmarks using passive markers attached to the skin. Eight markers are placed according to a modified version of recommended schemes in (Simon 2006), (Leardini 1999) and (Carson 2001). This configuration of the markers is relevant when the purpose is to measure navicula height and calcaneus angle. The low number of markers, the configuration of the markers and the fact that the gait is performed on a treadmill makes it possible to fully automate a safe identification of each marker in any image that contains the expected number of markers. This means that an initial identification is not needed.

2. HARDWARE

The used treadmill is from h/p cosmo. The markers are placed in such a way that they indicate the parts of the body which are important for the examination. The placing is carried out with special-purpose tools in correspondence with directions developed by specialists in orthopaedics. Both ball-shaped and flat circular markers are used. The reference points are made of a strongly reflecting material. The markers are fastened to the skin with double-adhesive tape.

Three cameras of the type Basler Scout scA640-74fm/fc (digital video camera produced by Basler Vision Technologies) are used. The optics is from Zeiss. The optics in camera 1 has a focal length of 16 mm. The optics in camera 2 and 3 has a focal length of 8 mm. FireWire (IEEE1394) is a standard interface concerning transmission of image data and commands between a computer and one or more digital cameras. This interface ensures real-time communication between computer and cameras. A PC with the following general properties is used: P4 – 3.2 Ghz, 2.5 Gb RAM, 74 Gb hard disk, graphics adapter: Matrox Millenium P650 PCI express 128 Mb.

2. SOFTWARE

StreamPix4 is a program developed by NorPix, Canada. The program stores simultaneous digital video recordings in real time in the RAM of the computer or on a connected hard disk. On the basis of the video recordings single images can be exported in a certain format (bmp, jpg).
PhotoModeler is a photogrammetric program which among other things comprises facilities concerning calibration of digital cameras. Fodex is a special program (prototype) developed with a view to simultaneous registration and analysis of the navicula movement and the change of the calcaneus angle during gait. Input to the program is single images in bmp-format from StreamPix4.

3. LAYOUT OF SYSTEM

The treadmill and the three cameras are placed in a laboratory as shown in Figure 1.

![Figure 1. The gait analysis laboratory of the Orthopaedic Surgery in Northern Jutland.](image)

Each camera is handled as follows:
- The focusing is adjusted
- The focusing ring is locked with screws
- Image sequences for calibration are recorded
- A calibration report is prepared with the program PhotoModeler
- The camera is fastened permanently to a shelf in a cupboard.

The three cupboards are fixed on a wall. The correct placing of the treadmill is marked with tape on the floor. The three cameras and the treadmill are marked out by means of a total station so that the camera axes concerning camera 2 and 3 are coincident and perpendicular on the camera axis concerning camera 1. The points 1, 2, 3 and 4 on the back of the lower leg are marked with ball-shaped markers, while the points 5, 6, 7 and 8 on the inner side of the foot are marked with flat circular markers, see Figure 2. Camera 3 is used for registration of points 1, 2, 3 and 4 as well as points 5, 6, 7 and 8, when the left foot is examined. Camera 1 registers point 1, 2, 3 and 4 no
matter which foot it is. In this way there are only two active cameras, when the registrations are made.

![Image: The fundamental contents of images from camera 1 and camera 3.]

**Figure 2.** The fundamental contents of images from camera 1 and camera 3.

![Image: Example of the actual contents of images from camera 1 and camera 3.]

**Figure 3.** Example of the actual contents of images from camera 1 and camera 3.

4. COLLECTION OF SIMULTANEOUS VIDEO SEQUENCES

Before the recordings are started with the StreamPix4 it is possible to adjust a large number of parameters. Of special importance is:

a. Parameters which influence the number of single images each second that will be recorded.

b. Parameters that influence whether the markers can be recognized in the collected images.

c. Parameters which concern the synchronisation of the video recordings.

After a number of tests a standard adjustment of the parameters has been found. The adjustment among other things implies that the images are cut from 656*494 to 656*300, see Figure 2, that the video recordings are stored in the RAM of the computer and that the video recordings are exported as single images in bmp-format. With the standard adjustment the number of single images each second is about 76. It has turned out to be very important that the lamps illuminate the object and are placed close to the two active cameras.
5. AUTOMATED MEASUREMENT IN IMAGES

Measurements in the collected images with the program Fodex are carried out according to the following procedure:

Image from camera 2 or 3:
   a. Search for pixels concerning markers in points 1, 2, 3, 4, 5, 6, 7 and 8
   b. Calculation of image coordinates \((r, s)_{2/3}\) for each marker
   c. Identification of markers
   d. Transformation of image coordinates \((r, s)_{2/3}\) to image coordinates \((x', y')_{2/3}\)
   e. First transformation of image coordinates \((x', y')_{2/3}\) to coordinates \((Y, Z)_{2/3}\)

Image from camera 1:
   f. Search for pixels concerning markers in point 1, 2, 3 and 4
   g. Calculation of image coordinates \((r, s)_{1}\) for each marker
   h. Identification of markers
   i. Transformation of image coordinates \((r, s)_{1}\) to image coordinates \((x', y')_{1}\)
   j. First transformation from image coordinates \((x', y')_{1}\) to coordinates \((X, Y)_{1}\)
   k. Second transformation from image coordinates \((x', y')_{2/3}\) to coordinates \((Y, Z)_{2/3}\)
   l. Second transformation from image coordinates \((x', y')_{1}\) to coordinates \((X, Y)_{1}\)

Procedure b and d as well as g and i are carried out according to parameters fixed by camera calibration with the program PhotoModeler. The image coordinates are corrected for radial lens distortion.

![Figure 4. Isometric depiction. Coordinate systems \((x'_1, y'_1), (x'_3, y'_3)\) and \((X, Y, Z)\).](image-url)
As will appear, the coordinates to points 1, 2, 3 and 4 are determined iteratively. At procedures k and l compensation is made for the fact that points 1, 2, 3 and 4 are not in the same distance from camera 1. The used method is thus as starting point monoplotting, but as points 1, 2, 3 and 4 are seen from two cameras, it is possible to determine these points in 3D (X, Y, Z). Points 5, 6, 7 and 8 are only seen from one camera and are therefore only determined in 2D (Y, Z). Please notice that the total procedure, including identification of markers, is automated. The mentioned coordinate systems are illustrated in Figure 2 and Figure 4.

6. CALCULATION OF 2D NAVICULA HEIGHTS

The navicula heights, NH₁ and NH₂, calculated cf. Y and Z to point No. 5, 6, 7 and 8. NH₁ is the length of the normal through 7 to the line 5-8. NH₂ is the length of the normal through 7 to the line 6-8. See example in Figure 5.

7. CALCULATION OF CALCANEUS ANGLE

The 3D and 2D calcaneus angle is calculated cf. X, Y and Z to point No. 1, 2 and 3. The 2D calcaneus angle is compensated for foot angle. First a rotation of points 1, 2 and 3 is carried out according to:

\[
\begin{bmatrix}
Z_1 & Z_2 & Z_3 \\
X_1 & X_2 & X_3
\end{bmatrix}_{rot} =
\begin{bmatrix}
Z_1 & Z_2 & Z_3 \\
X_1 & X_2 & X_3
\end{bmatrix}
\begin{bmatrix}
\cos f & -\sin f & 0 \\ 
\sin f & \cos f & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
Z_1 & Z_2 & Z_3 \\
X_1 & X_2 & X_3
\end{bmatrix}
\]

(1)

The foot angle f is indicated positively if the foot is pointing outwards, negatively if the foot is pointing inwards. The foot angle must, with the present version of the system, be determined manually, before the video sequences are recorded. The 2D calcaneus angle, designated CA₂D, is thus calculated cf. Xrot and Y to points 1, 2 and 3, see example in Figure 6. Please notice that the foot angle thus has the same value in all calculations of CA₂D.
9. AUTOMATED GAIT ANALYSIS

With Fodex it is moreover possible to make an analysis of changes in the navicula height and the calcaneus angle in the stance phase, which is here defined as the time from the heel touches the treadmill (heel strike) till the toe is lifted from the treadmill (toe off). The user has to identify the images which concern heel strike and toe off for the first three steps. On this basis a (Equation 2) is determined, which is the average number of images from heel strike to toe off. Hereafter all the other steps are identified automatically. This is possible because the navicula height expressed by NH\textsubscript{1} has an easily identifiable maximum at toe off in each step, see Figure 8.

Immediately after heel strike a small local maximum often occurs. The heel strike in each step is found by analyzing three images with the numbers bi-1, b\textsubscript{i}, and bi+1, where bi is calculated as:
In this way all measurements concerning the stance phase in each step are identified. These measurements are subjected to a closer analysis. In the following the analysis concerning the navicula height is described. The time from heel strike till the navicula height reaches its minimum is called the drop phase. The difference between the minimum navicula height \( \text{NHL}_1 \) and the navicula height \( \text{NHU}_1 \) at heel strike is called \( \Delta \text{NH}_1 \). In this way \( \Delta \text{NH}_1 \) describes how much the navicula (point 7) moves by a maximum along the standard to the line through point 5 and point 8 within the step in question. The analysis further comprises the relation between the drop phase and the stance expressed in %, \( \text{NHL} \%_1 \) as well as the speed of the movement \( \text{NHV}_1 \). A corresponding analysis is made concerning the calcaneus angle, \( \text{CA}_{2D} \). An overview of the used abbreviations and their definition appears from Table 1.

\[
b_i = b_{\text{tow-off}} - a
\]  

\[ (2) \]

Table 1. Parameters and abbreviations.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{NH}_1 )</td>
<td>Navicula Height</td>
</tr>
<tr>
<td>( \text{NHU}_1 )</td>
<td>Navicula Height Unloaded is the navicula height at heel strike.</td>
</tr>
<tr>
<td>( \text{NHL}_1 )</td>
<td>Navicula Height Loaded is the minimal navicula height measured during the stance phase.</td>
</tr>
<tr>
<td>( \Delta \text{NH}_1 )</td>
<td>Navicula drop, ( \Delta \text{NH} ) is measured as the range from navicula height at heel strike to the minimal height measured during stance phase (( = \text{NHU} - \text{NHL} )).</td>
</tr>
<tr>
<td>( \text{NHL} %_1 )</td>
<td>Navicula drop, ( \Delta \text{NH} ) is measured as the range from navicula height at heel strike to the minimal height measured during stance phase (( = \text{NHU} - \text{NHL} )).</td>
</tr>
<tr>
<td>( \text{NHV}_1 )</td>
<td>Navicula Height Velocity is navicula drop velocity in mm / sec from heel strike to ( \text{NHL} ) (Drop velocity from ( \text{NHU} ) to ( \text{NHL} ))</td>
</tr>
<tr>
<td>( \text{CA}_{2D} )</td>
<td>Calcaneus Angle</td>
</tr>
<tr>
<td>( \text{CAU}_{2D} )</td>
<td>Calcaneus Angle Unloaded (= Calcaneus Angle heel strike)</td>
</tr>
<tr>
<td>( \text{CAL}_{2D} )</td>
<td>Calcaneus Angle Loaded is the maximum calcaneus angle measured during the first 90% of stance phase (= Maximal Calcaneus Angle).</td>
</tr>
<tr>
<td>( \Delta \text{CA}_{2D} )</td>
<td>Calcaneus Angle range is measured as the range from calcaneus angle at heel strike to maximum calcaneus angle (= ( \text{CAU} - \text{CAL} )).</td>
</tr>
<tr>
<td>( \text{CAL} %_{2D} )</td>
<td>Calcaneus Angle Loaded as percentage of stance phase is the time to maximum calcaneus angle.</td>
</tr>
<tr>
<td>( \text{CAV}_{2D} )</td>
<td>Calcaneus Angle Velocity is calcaneus angle velocity in degrees / sec from heel strike to ( \text{CAL} ) (CA velocity from ( \text{CAU} ) to ( \text{CAL} )).</td>
</tr>
</tbody>
</table>

10. ACCURACY AND PRECISION

The accuracy and precision of the system is tested by measuring 8 markers placed on a wooden leg. The test is based on 2*1000 images provided on the basis of two simultaneous video sequences of the wooden leg recorded with camera 1 and camera 3. The wooden leg was moved by hand during the recording. The speed of the treadmill was 4 km/h. The video sequences were recorded with 76 frames each second. The physical conditions during the measurements are in this way highly identical with the conditions when measuring on a human leg. The difference is
only that the wooden leg is stiff, i.e. the navicula height and the 3D calcaneus angle are constant. The true values concerning NH₁ and CA₃D are determined by means of a slide gauge. The accuracy and precision of the measurements appear from Table 2.

Table 2. Fodex. Accuracy and precision.

<table>
<thead>
<tr>
<th></th>
<th>Wooden leg accuracy</th>
<th>Wooden leg precision</th>
<th>Human leg precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₁</td>
<td>0.3 mm</td>
<td>0.3 mm</td>
<td>NH₁</td>
</tr>
<tr>
<td>NHU₁</td>
<td>0.5 mm</td>
<td>1.5°</td>
<td>NH₁</td>
</tr>
<tr>
<td>NH₁</td>
<td>0.8 mm</td>
<td>0.9 mm</td>
<td>ΔNH₁</td>
</tr>
<tr>
<td>CA₃D</td>
<td>0.3°</td>
<td>0.3°</td>
<td>CA₃D</td>
</tr>
<tr>
<td>CAU₂D</td>
<td>1.5°</td>
<td>1.7°</td>
<td>CAU₂D</td>
</tr>
<tr>
<td>CA₂D</td>
<td>0.8°</td>
<td>1.7°</td>
<td>CA₂D</td>
</tr>
</tbody>
</table>

Results from an experiment that comprises 51 independent sessions concerning 17 persons show that at heel strike and toe off the navicula height and the 2D calcaneus angle can be determined with a precision as shown in Table 3. Each session comprises in average 18 steps. The standard deviations concerning NH₁ and NHL₁ for legs are higher than the standard deviation concerning NH₁ for wooden legs. This is due to the movements of the skin in relation to the marked parts of the body.

The standard deviations concerning CAU₂D and CAL₂D for legs are higher than the standard deviation concerning CA₃D for wooden legs. This is due to the movements of the skin in relation to the marked parts of the body and, as regards CAU₂D, that the foot angle is not constant at heel strike in all steps.

11. TIME CONSUMPTION

A typical measurement session comprises about 25 steps. The speed of the treadmill is 4 km/h. The analysis is carried out on the basis of 2000 images recorded with camera 1 and 2000 images recorded with camera 3. The time consumption is then typically as shown in Table 3.

Table 3. Fodex. Time consumption of a typical measurement session.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction and informed consent</td>
<td>3</td>
</tr>
<tr>
<td>Measurement of foot angle</td>
<td>1</td>
</tr>
<tr>
<td>Measurement of FPI score</td>
<td>1</td>
</tr>
<tr>
<td>Putting on markers</td>
<td>3</td>
</tr>
<tr>
<td>Adaption to treadmill</td>
<td>6/14</td>
</tr>
<tr>
<td>StreamPix4, recording of video sequences</td>
<td>1</td>
</tr>
<tr>
<td>StreamPix4, conversion from seq-format to bmp-format</td>
<td>2</td>
</tr>
<tr>
<td>Fodex, automated measurement in images</td>
<td>8</td>
</tr>
<tr>
<td>Fodex, indication of heel strike and toe off</td>
<td>2</td>
</tr>
<tr>
<td>Fodex, automated gait analysis</td>
<td>3/16</td>
</tr>
<tr>
<td>Total time consumption</td>
<td>30</td>
</tr>
</tbody>
</table>
12. CONCLUSION

With the developed software the navicula height can be determined with a standard deviation of 0.5 - 0.8 mm. The calcaneus angle can be measured with a standard deviation of 0.8 - 1.5 degrees. The next phase in the project should focus on determining the movement of the navicula in 3D and on investigating alternative procedures/methods that may produce more precise and reliable measurements of the calcaneus angle at heel strike.

Seen in relation to the large quantity of data materials collected in each measurement session the time consumption is extremely low. The next phase in the project should focus on reducing the time consumption of measurements in images.

REFERENCES


