D1.3 Validation of the marker-free movement analysis method

Abstract
The 4-D scanner registers a surface image of the object changing in time, then calculates its kinematics. It is intended to be used in the project to capture kinematics of human lower extremities and feed the TLEM model. The desired output should be similar in quality and quantity to the output of currently used Vicon motion capture system. Our goal in this task (WP1.3) is to confront the 4-D scanner’s output with Vicon’s, evaluate systematic errors, define flaws of the scanner’s measurement or analysis process and point direction of further improvement.

A simultaneous Vicon and 4-D scanner measurements have been run to provide input for the validation. The 4-D scanner enabled extraction of thigh and shank long axes, which lead to evaluating angles essential for hip abduction trial and gait trial, the two trials taken into account due to the first one’s simplicity and the second one’s complexity.

The validation has been based on thigh abduction, thigh flexion and knee flexion angles (angles defined further). In the hip abduction trial the thigh abduction angles for the abducted leg calculated by the 4-D scanner are very similar to these presented by Vicon (3° RMS error) while for gait trial two sources of substantial systematic errors have been detected (resulting in RMS error at level of 5-10°). The 4-D scanner has difficulties when processing frames where one of the legs is occluding the other, in which case the knee flexion angle is systematically underrated, and frames where a leg is straight and it’s hard to determine the plane of knee flexion.

Improvement plans are presented in the last section of the report (page 20). The new hardware configuration is going to be used in the next measurements. It will be a frontal-rear configuration with two cameras per projector in a vertical layout and is expected to both stabilize the kinematic segment’s axis evaluation and widen the measurement scope (number of captured kinematic variables) by extending the measured surface.
The measurement

The validation measurements have been performed in the rehabilitation laboratory at Radboud University Nijmegen Medical Centre, Netherlands, in mid July 2011. The laboratory is equipped with the Vicon system along with pressure mats mounted within a long walkway. The 4-D scanner has been brought to Nijmegen from the Warsaw University of Technology, Poland.

The measurements required the laboratory to be darkened. The 4-D scanner used its projectors to illuminate the measured volume with blue and red stripes while the Vicon system illuminated the scene with its infrared illuminators. The scene was then registered by six of Vicon’s and two of the scanner’s cameras – Vicon ran at 120Hz and the 4-D scanner at 60Hz. Both systems were launched and stopped on a manual basis and operated by qualified personnel.

For the validating measurements five subjects have been employed. Each subject was equipped with white matt tights to increase optical contrast of the visible stripes and to reduce skin’s influence on their local amplitude. Subjects wearing tights had then a 24-piece marker-set installed on their lower body, according to Vicon’s Plug-In-Gait specification.

Each subject performed several isolated joint movements, including knee flexion, hip flexion and hip abduction, as well as several activities of daily living, including comfortable-speed walking and standing up from a chair. Measurements themselves took about 3hrs and the whole measurement session along with the initial installation and calibration took four days to complete.

Kinematic variables

Two trials have been analyzed – the least and the most complex in terms of surface data analysis. In the hip abduction trial we relatively isolated the hip abduction movement. Both legs are fully visible and are both measured and processed well. The gait trials are the most cumbersome for kinematic analysis. They require manual preprocessing and introduce coarse errors which project onto kinematic variables as noise or systematic deviation.

Illustration 1. Analyzed trials. Left: hip abduction trial sample; right: gait trial sample.
For these two trials the three trial-specific essential angles have been evaluated. For isolated hip abduction trial the thigh abduction angle has been defined in a simplified manner as follows:

**thigh abduction angle** – angle between the *thigh long axis* projected on the *coronal plane* and the *global vertical axis*

For the gait trials, we evaluate thigh and knee flexion angles, which we define as follows:

**thigh flexion angle** – angle between the *thigh long axis* projected on the *sagittal plane* and the *global vertical axis*

**knee flexion angle** – absolute angle between the *thigh long axis* and the *shank long axis*

The definitions are highly simplified (vs. standard terminology), because they assume no pelvic tilt/rotation/obliquity nor hip rotation takes place. This is due to current inability to extract these variables from surface data. Plans for improving completeness of the kinematic description are presented at the end of the report.

**Evaluation method**

The kinematic variables defined above are calculated from results of both measurement tools, the Vicon system and the 4-D scanner. Because the output of each system is different, the method of extracting the angles differs and is described in the following sections.

**4-D scanner**

The method presented herein is built on an assumption that the values of lower extremities segment angles may be estimated based on the central lines (mid-lines) of limb segments. The algorithm described below is aimed at estimating the time-variant parameters of thigh and shank local coordinate systems (for both legs) in the global coordinate system.

*Step 1: Sequence loading and filtering*

In the first step a time sequence of point clouds is loaded into memory. As this data comes directly from the measurement system it may contain various types of noise as well as larger erroneous surface patches that had been either miscalculated or do not belong to the subject (e.g. floor, walls). In the proposed method the noise is removed automatically while larger surface areas need to be removed manually.

*Step 2: Slicing in vertical direction*

The algorithm uses a slicing operation several times. The first slicing is along the vertical axis of the global coordinate system. It is used to determine the crotch level. The crouch level is determined based on the distance between the two largest point groups in a given slice. Slices below the crouch level are assumed to belong to the legs, while slices above the crouch level fall into trunk category.

Illustration 3. Point groups created based on horizontal slices. It may be seen that groups in the top thighs region have the same color for both legs (they have not been properly assigned to legs yet).
**Step 3: Allocating points to left and right leg**

Points from slices that are below the crouch level are grouped according to the leg they belong to. Moreover, at this step a crotch level adjustment is performed. It corrects for point clouds where the legs touch each other and (especially for thigh slices) the gap between them is too small.

**Step 4: Calculating legs’ central lines**

For each point group that belongs to a leg the best fit circle is calculated. These circles lay on horizontal planes parallel to slices. For each leg a line is fit to the circles’ centers (the centers from upper and lower 20% of slices are neglected due to common radius calculation errors; this will be referred later as top and bottom margins). The line is the central line of the leg. Additionally, the best fit plane (BFP) is calculated for each leg based on these circle centers. It is later assumed that the knee flexion axis is perpendicular (normal) to the BFP.

**Step 5: Slicing along legs’ central lines**

The second slicing iteration is performed along each leg’s central line. In this step some points from the torso segment may be added to legs (e.g. for high hip abduction angles).

**Step 6: Finding knee slices**

The knee slice is found based on an assumption that if a leg is divided at that slice and two lines are fit to circle centers respectively above and below the knee slice then the total fitting error should be the lowest when compared to division at other slices.

Illustration 4. Point groups created based on segments’ temporary central lines.
Step 7: Calculating temporary central lines of thighs and shanks
Based on knee slices the legs are divided into thigh and shank segments. For each leg and for each segment a new segment’s temporary central line is calculated. The temporary central lines are calculated without the top and bottom margin slices.

Step 8: Slicing along segments’ temporary central lines
The last slicing operation is performed for each segment along its temporary central line.

Step 9: Calculating final central lines of thighs and shanks
The final central line of each segment is calculated based on the slices. Circle centers belonging to top and bottom margins as well as to knee region (top 20% shank and bottom 20% thigh) are neglected in this operation.

The segments’ central lines are projected onto the BFP. The new lines are considered segments’ vertical axes. The BFP normal vector is considered segments’ (left) side axis. The forward axis is calculated as cross product of the axes mentioned.

Step 10: Estimating segment angles
The thigh angles are extracted from transformation matrices that link the global coordinate system axes with the segment’s local coordinate system axes. The order of rotations is coherent with Vicon’s one (Y-X-Z = Flex-Abd-Rot).

The only rotation allowed for knees is flexion. The flexion angle is calculated from the projection of thigh and shank axes on the leg’s best fit plane.

Illustration 5. Final central lines of thighs and shanks.
Limitations
The algorithm described herein is based on segment central lines which are not bones. We will try to find a correlation between them.

The surface data captured in Nijmegen does not cover neither pelvis nor feet. Pelvis is required to calculate local hip angles (pelvis-to-thigh coordinate system transformation).

For low knee flexion angles the knee slice is sometimes estimated (few slices too high or too low). The impact on knee angle estimation is quite small, however.

For low knee flexion angles the best fit plane is often miscalculated which leads to large errors in thigh rotation angle estimation. Perhaps a front-back measurement system set-up will correct this problem.

Vicon
The kinematic data from measurement session at RUNMC have been available as c3d files, one per trial. The files contain raw measured labeled markers positions and time series of output variables of the Vicon’s Plug-In Gait module.

The steps taken to extract above-defined simplified angles are presented in Illustration 7. As an input there are angles highlighted in Illustration 6, i.e. all pelvis, hip and knee angles. According to Plug-In Gait manual, each labeled angle triple defines a YXZ Cardan transformation from parent coordinate system to segment’s local coordinate system. Given local frames’ hierarchy (described in the manual), their vector representation has been calculated. The following paragraphs describe the calculus in detail.

Illustration 6. Kinematic and kinetic variables calculated by Plug-In Gait. The marked variables have been used to compute angles being compared during validation.

1 PIGManualver1.pdf, pages 49+; available online at http://goo.gl/pFGG5 (PDF) or http://goo.gl/NsyVq (Scribd)
2 see article on Wikipedia: http://goo.gl/h8po9
Cardan angles to basis versors

The Plug-In Gait application exports Cardan angles to express local coordinate systems. They have to be resolved to global bases' versors. Two elements need to be known to achieve it – the way Cardan angles are understood for this specific software and the hierarchy of coordinate systems.
Cardan angles are Euler angles describing rotation component of geometric transformation between systems as a sequence of three rotations around well-defined temporary axes. As Plug-In Gait manual states, Vicon system rotates a local frame around its Y axis, then its resultant X axis and finally the resultant Z axis to transform parent to child system$^3$:

$$E_2 = R_Z \cdot R_X \cdot R_Y \cdot E_1$$

$$E_i = \begin{bmatrix} v_{i,x} \\ v_{i,y} \\ v_{i,z} \end{bmatrix} \in \mathbb{R}^{3 \times 3}$$

$$R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_x & -s_x \\ 0 & s_x & c_x \end{bmatrix}$$,  
$$R_Y = \begin{bmatrix} c_y & 0 & s_y \\ 0 & 1 & 0 \\ -s_y & 0 & c_y \end{bmatrix}$$,  
$$R_Z = \begin{bmatrix} c_z & -s_z & 0 \\ s_z & c_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_q = \sin \alpha_q, c_q = \cos \alpha_q$$

where Cardan angles $$(\alpha_x, \alpha_y, \alpha_z)$$ define a transformation of frame $E_1$ into frame $E_2$.

The hierarchy of segments’ local coordinate systems is defined in the documentation. Pelvis frames (strangely, pelvis frame is split into two) are defined in relation to the global coordinate system, thighs are relative to pelvis and shanks are relative to thighs. Since the top frame (pelvis frames) is a descendant of the frame described by an identity matrix, the propagation of frames looks like in the Illustration 9.

Exemplary resolved coordinate systems are shown in the Illustration 10. To see local frames in motion, please proceed to http://goo.gl/pa8e6, where you can find downloadable and browser-viewable animations.

Illustration 9. Hierarchy of segments’ local frames. Boxes are segments with their names. Arrows point child segments and are labeled with angle series within c3d files used to transform parent to child frame.

$^3$ rotation matrices taken from http://goo.gl/STppp
Illustration 10. Segments’ local frames for a gait trial in a form of basis vectors with some of the markers visible for viewing convenience. Axes are visualized with RGB colors — red, green and blue for X, Y and Z, respectively.

Angles extraction

The synthetic angles were calculated according to the following formulas. Two globally understood axes are used — thigh long axis \( u = v_{TH,z} \in \mathbb{R}^3 \) and shank long axis \( w = v_{SH,z} \in \mathbb{R}^3 \), where \( v_{*,z} \) is a z-axis of a particular segment’s local frame.

- Hip abduction angle: \( \alpha_{HA} = \tan^{-1}(u_x/u_z) \) \hspace{1cm} (1)
- Hip flexion angle: \( \alpha_{HF} = \tan^{-1}(u_y/u_z) \) \hspace{1cm} (2)
- Knee flexion angle: \( \alpha_{KF} = \cos^{-1}(u_z \cdot w_z) \) \hspace{1cm} (3)

Illustration 11. Sample angles series extracted from Vicon results for the gait trial.
Results comparison

Three hip abduction trials and three gait trials have been processed for the present document. The shortage of data is a result of error appearing in some of the measurements (for both Vicon and 4-D system) and time consumption of the processing, which is partially automatic and partially manual (e.g. hip abduction sequence of 1500 frames produces automatically series of angles values over a night). We do have more workable data but limited ourselves to rational minimum over which we can discuss the methods we have used.

Vicon results were processed in Matlab-like GNU Octave and 4-D scanner data were processed with two pieces of custom-made software and post-processed with Octave. In both cases the calculated series of angles values were properly scaled in time domain since the measurement frame rates were known. Thus the results horizontal alignment was only a matter of shifting and not scaling. Vertical alignment and scaling has not been performed.

Each sequence has been assigned an RMS error \( e(f_1, f_2) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} (f_1(k) - f_2(k))^2} \) and a relative error power \( r(f_1, f_2) = \frac{\sum_{k=1}^{N} (f_1(k) - f_2(k))^2}{\sum_{k=1}^{N} f_1(k)^2} \).

Hip abduction

Three sequences have been prepared. For a hip abduction trial we evaluate the hip abduction angle for both legs. The series have been aligned horizontally arbitrarily since no objective time point can be spotted in this trial.

Illustration 12. Thigh abduction angle for subject 3. Right thigh: \( e = 9.1^\circ, r = 19\% \); left thigh: \( e = 9.3^\circ, r = 220\% \).

Illustration 13. Thigh abduction angle for subject 4. Right thigh: \( e = 3.4^\circ, r = 2.0\% \); left thigh: \( e = 6.0^\circ, r = 410\% \).
First two cases are satisfactory. The third has been brought here to present a problem we have faced. During the movement the subject’s shank is going outside of the calibrated volume, the points were missing and shank axis could not be properly evaluated or could not be evaluated at all. The risk of it is avoidable and it will be avoided in future measurements.

Gait

For each of three gait trial sequences a hip flexion and knee flexion angles have been evaluated. Due to legs’ overlapping, processing of gait sequences is fairly difficult. We experience coarse errors, causes of which are mostly identified. Most problems will be solved by rearranging the measurement physical configuration.

In the following figures the time scale is substituted with gait phase bounds. Full labels are: Heel Strike, Toe Strike, Mid-Stance, Heel Off, Toe Off and Mid-Swing\(^4\). Phases were manually fixed by a lay operator and may be inaccurate. The horizontal alignment used two Heel Strike points per sequence evaluated for Vicon and 4-D result series.

\(^4\) If the terminology is wrong or outdated, please provide us with a preferred reference terminology source.
Illustration 15. Thigh flexion angle for subject 1, trial ‘gait_02’. Right thigh: e = 6.5°, r = 18.4%; left thigh: e = 2.8°, r = 3.1%.
Illustration 16. Knee flexion angle for subject 1, trial ‘gait_02’. Right knee: $e = 10.3^\circ$, $r = 11.8\%$; left knee: $e = 9.8^\circ$, $r = 10.4\%$. 
Illustration 17. Thigh flexion angle for subject 2, trial ‘gait_07’. Right thigh: \( e = 5.0^\circ, r = 10.5\% \); left thigh: \( e = 6.1^\circ, r = 14.6\% \).
Illustration 18. Knee flexion angle for subject 2, trial 'gait_07'. Right knee: $e = 6.3^\circ$, $r = 6.3\%$; left knee: $e = 7.0^\circ$, $r = 5.9\%$. 
Illustration 19. Thigh flexion angle for subject 5, trial ‘gait_01’. Right thigh: $e = 5.1^\circ$, $r = 14.3\%$; left thigh: $e = 5.6^\circ$, $r = 16.6\%$. 
Illustration 20. Knee flexion angle for subject 5, trial ‘gait_01’. Right knee: $e = 7.5^\circ$, $r = 6.4\%$; left knee: $e = 6.6^\circ$, $r = 6.5\%$.

The following tables hold error estimates of the series presented above. The RMS of the error describes the overall series’ fitting mismatch while error relative power expresses the amount of mismatch in relation to reference signal’s capacity.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Subject</th>
<th>Error relative power</th>
<th>Root of mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>right</td>
<td>3</td>
<td>19.0%</td>
<td>9.1 deg</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.0%</td>
<td>3.4 deg</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.5%</td>
<td>7.8 deg</td>
</tr>
<tr>
<td>left</td>
<td>3</td>
<td>220.0%</td>
<td>9.3 deg</td>
</tr>
</tbody>
</table>
There are two main sources of errors for the gait trial and refers to how the two-directional 4-D scanner with its current configuration works:

1. During gait, the rear leg is visible only to one of two cameras. Circles approximating thigh’s and shank’s sections are very erroneous – not only the noise is higher, but also the circles are bigger and both thigh and knee flexion angles are systematically underrated.

2. Whenever the knee is in ‘neutral’ angle (the lowest possible), the thigh and shank axes common plane is hard to determine and the knee flexion angle is overvalued. The error would be visible on the plots if Vicon wouldn’t have produced even more false results. As it is shown in the Illustration 21, shank axis is wrong and significantly overrates absolute knee angle.
Illustration 21. A Vicon gait result frame presenting erroneous right shank long axis orientation. Full animation online at http://goo.gl/72a9H.

Kinematic description improvement
To address the shortage of surface data and systematic joint angle estimation errors a different hardware configuration of the 4-D scanner is planned. The schematic illustrating the following description is shown in the Illustration 22.

The frontal and rear direction of measurement will be used. The measured surfaces won’t be fully connected which is somewhat a disadvantage, but at the same time surface coverage will improve and circles approximating legs transverse sections will be more correct. Legs will not be occluding each other which means axes will be evaluated based on at least two (and at most four) single-directional surfaces. After such reconfiguration more authentic angle values will be produced.

Moreover, additional cameras are going to be employed, one aimed slightly downwards, another aimed slightly upwards. Along with calibration on a larger volume, it will enable measurement of trunk and feet, thus evaluation of additional joint angles. Detectors are planned to cover the following regions (with gait trial in mind):

<table>
<thead>
<tr>
<th>Detector</th>
<th>Position</th>
<th>Target region</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Rear top</td>
<td>Buttocks, temporarily thighs and shanks</td>
</tr>
<tr>
<td>D2</td>
<td>Rear bottom</td>
<td>Buttocks, lower back, temporarily thighs and shanks</td>
</tr>
<tr>
<td>D3</td>
<td>Frontal top</td>
<td>Feet, temporarily thighs and shanks</td>
</tr>
<tr>
<td>D4</td>
<td>Frontal bottom</td>
<td>Abdomen, temporarily thighs, shanks and feet</td>
</tr>
</tbody>
</table>
Summary

In the present document we declared the validation strategy we have taken, described in detail the method being used for evaluation of three kinematic variables – thigh flexion angle, thigh abduction angle and knee flexion angle – and presented results of systems’ output comparison. The comparison led to defining sources of systematic errors, mostly related to insufficiency of measured surface, which are going to be eliminated or at least limited by the new setup presented in the document. The new configuration employs additional cameras and focuses on surface coverage, both frontal and rear. The next measurements will use this configuration and the appendix reporting 4-D scanner’s output kinematic description improvements will be submitted.