KINECT AND SHIMMER SENSORS IN MOTION ANALYSIS IN HEALTH APPLICATIONS

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Abstract: Motion capture systems based on different physical principles and sensor elements become moderate in price and mobile in application. New application fields have been developed. Motion capture and analysis is used in physiotherapy, geriatrics or public sports. In this paper three different types of motion capture systems are investigated with respect to their adaptability to health applications: the OptiTrack-Motion Capture System, the Kinect of Microsoft and SHIMMER sensors. Human gait was measured using all three systems and the obtained data were compared. In further tests the gait of volunteers and patients were captured with Kinect and two scores evaluating their motion capability were calculated.

1 INTRODUCTION

The story of gait analysis is very old and goes back to the latter years of the 19th century. The German medics Braune and Fischer performed different gait studies, especially in the military environment funding the investigations. They analyzed the human gait with photogrammetry. For a very long time photogrammetry was the gold standard (Woltring, 1989; Cappozzo and Tosi, 1989).

The data were taken manually from observations, measuring various characteristics of walking patterns like length, height or duration of one step, width of one stride, the duration of the stance or the swing phases. Perry described the normal and pathological gait and developed the observing gait analysis (Gronley and Perry, 1984; Perry, 1995; Perry, 2010; Goetz-Neumann, 2003). Her research in gait analysis was addressed to improve the lifestyle of handicapped patients (R. L. A. National Rehabilitation Center, 2009). To automate the measurement, active and passive markers were attached to well-defined positions. Two dimensional kinematic analysis was realized, e.g. using 312 Hz LEDs as markers recorded by cameras (Van Best, 1984).

Morris et al. (Morris and Lawson, 2009) reviewed and evaluated techniques, such as the use of force plates (late 1960s), of accelerometers (1970s) and the first motion capture systems (1980s). Their overview included modern technologies like video cameras, optoelectronic systems, electromyography (EMG), force plates and shoes as well as inertia sensors (accelerometers and gyroscopes).

Motion capture was performed using camera systems combined with other sensors. Nowadays motion capture systems use small ball-shaped markers. Infrared cameras receive the reflected light transmitted by LED rings. The 3D-positions of markers attached to the human body are calculated using the data from a number of different infrared (IR) cameras. Alternatively to external vision systems, sensors are directly attached to well-defined locations on the human body. The data measured by accelerometers and gyroscopes are transferred wireless, e.g. using Bluetooth connections, to the supervising computer system. The SHIMMER package provides integrated 9DoF (Degrees of Freedom) sensors including 3D-accelerometer, -gyroscope and -digital compass as well as physiological sensors like EMG or electrocardiography (ECG) (Shimmer, 2011). The 3D-positions of the sensors are determined off-line, calculating them step by step starting from their initial 3D-positions. Liu et al. (Liu, 2009) combined accelerometer and gyroscope data for quantitative gait analysis. Greene et al. (Greene, 2010) extracted temporal gait parameters from the angular velocity of the shank. Both papers discussed the necessity of recalibration during the evaluation and compared their

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results with optical motion capture systems.

Novel systems, like the Kinect[1] or Wii Remote[2], work without any markers. The Kinect uses a combination of a RGB camera and a depth sensor. The Wii Remote is based on accelerometers and optical sensors which is also used for motion capturing (Wang and Huang, 2008).

Stationary technologies and expensive, high-end equipment have been used already for a long time in university hospitals, scientific institutes and specialized cinema studios for different purposes. Normal hospitals, nursing homes, physiotherapy or popular sports centers need well-performing, affordable and mobile sensor systems to capture and analyze movements sufficiently accurate. Automated procedures can support physiotherapists, nurses and doctors in geriatric care units as well as coaches in sports.
In this paper the OptiTrack-Motion Capture System, the Kinect and SHIMMER sensors are investigated with respect to their adaptability to health applications. A number of experiments was done to compare the three systems in human gait analysis, to test the Kinect and SHIMMER sensors for the evaluation of motion capabilities as well as to record the execution of sports exercises.

Which values have to be calculated from the measured data? Regarding to health applications the following values may be important:

- 3D-coordinates of the joint centers for the kinematic body motion analysis,
- joint angles for the analysis of joint mobility,
- length of one step and height of one swing, length and width of one stride, walking velocity and others like Tinetti (Tinetti, 1986) or fitness scores.

2 SYSTEMS AND METHODS

In this section the used systems are described and methodological aspects of the locomotion model are explained.

2.1 Motion Capture System (MoCap)

Optitrack[3] consists of 12 infrared cameras and two different software applications: 'Arena' for full body motion capture and Tracking Tools for body rigging with any desired number of tracking markers. All cameras are active emitting infrared light via a LED circle around their lenses. The body markers are highly reflective and the optical system is high sensitive to the infrared spectrum. It is important that each camera records solely the tracking markers of the tracked person and not the infrared components of the sunlight or the IR light emitted by the other cameras. 'Arena' records the input of all cameras simultaneously and computes a so-called point cloud in real time. The computation needs some preprocessing (calibration, T-pose, adjustment of the skeleton model) (Nat. Point Inc., 2011). The recorded data can be "trajectorized", i.e., converted into other formats which includes all data of the model and the derived tracking joint angles (bvh-file) or the 3D-positions of the tracking markers (fbx-file).The major advantage of vision systems is that the 3D-positions are determined continuously in the inertial coordinate system, while a disadvantage is the restricted area of recording mostly measuring less than 5 by 5 m.

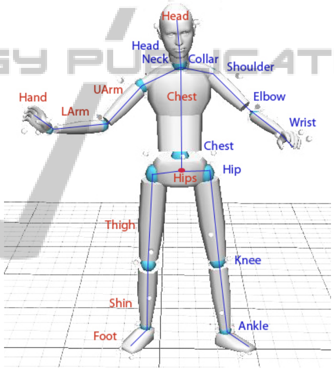

Figure 1: Human body model, markers, skeleton, names of joints (blue) and links (red).

OptiTrack uses 34 markers attached to the human body (see Fig. 1). The 3D-positions of these points are used to calculate the optimal set of the 3D-positions of the centers and the 3D-angles of the 18 joints as well as the absolute 3D-position and orientation of the reference point (placed on the hip). The kinematical model of the locomotor system consists of 23 rigid bodies (links) connected by 18 spherical joints. The fixed characteristics of the skeleton are predefined during the calibration procedure. The kinematical model is given by:

$$R^*_k = R_k R^*_{v_k}, \qquad k = 1,\ldots,18 \tag{1}$$

$$r^*_k = R^*_k r_k + r^*_{v_k}, \qquad k = 1,\ldots,18 \tag{2}$$

where R^*_k is the absolute rotational matrix of link k, r^*_k the absolute position vector of the joint k, R_k the rotational matrix of the joint k, r_k the dimension vector of link k, v_k the index of the predecessor and R_0, r_0 the orientation and position of the reference point/link.

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[1] http://en.wikipedia.org/wiki/Kinect

[2] http://en.wikipedia.org/wiki/Wii_Remote

[3] http://www.naturalpoint.com/optitrack/

The rotational matrix R_k is calculated from the angles of joint k using the well-known relationship:

$$R(\alpha,\beta,\gamma) = M_\gamma M_\beta M_\alpha \tag{3}$$

where $M_\alpha, M_\beta, M_\gamma$ are the rotation matrices with α, β, γ as joint angles around the x, y, z axes, respectively.

2.2 Microsoft Kinect Sensor (Kinect)

The Microsoft Kinect sensor system consists of the depth sensor, the RGB camera, the microphone array and the motor [4]. The software development kit (SDK) for Windows 7[5] provides access to the raw sensor data streams, the skeletal tracking and the automatic calibration. Using this kit $C++$, *C#* or VB applications can be developed . The skeletal tracking immediately delivers the 3D-positions of 20 points on a fictive skeleton (see Fig. 2). The characteristic dimensions of the skeleton (model) are determined during calibration guided by the software[6].

Figure 2: Video Stream (a), Depth Stream (b) and Skeleton rendered in the full body (c) received from Kinect. In (a) and (b) the skeleton is added, in (a) the position of some markers used in MoCap and the Position of one SHIMMER sensor are shown. In (c) the 20 skeleton points are named.

The joint angles are calculated from the 3D-coordinates of the corresponding joints. For example, the angle λ of the left knee is determined from vectors v_{KH} and v_{AK} where v_{KH} is directed from the knee to the hip and v_{AK} is directed from the ankle to the knee. The cross product of both vectors shows the direction of the temporary joint axis e_k and the normalized product gives the sine of the joint angle λ:

$$v_{AK} \times v_{KH} = |v_{AK}|\,|v_{KH}|\,e_k \sin\lambda \tag{4}$$

2.3 SHIMMER Sensors (SHIMMER)

The SHIMMER[7] platform is a wireless sensor platform with a small form factor that supports mobile applications. All sensors are characterized by low power consumption and weight. The measured data can be stored off-line on a microSD or streamed in real time using Bluetooth or 802.15.4 radio. SHIMMER offers products for the categories kinematics (accelerometer, gyroscope and magnetometer), biophysical (ECG, EMG) and ambient (GPS). All sensors consist of a baseboard and a daughterboard. The baseboard acts as the main board with an on-board microcontroller, wireless communication modules, microSD slot and an integrated three-axis accelerometer (Shimmer, 2011).

The calibration of the sensor can be executed using the 'Shimmer 9DoF Calibration Application' (Ferraris and Parvis, 1995). The streaming of up to four sensors concurrently has been made possible with the 'Four Shimmer Write'-program. This application handles preprocessed data.

The vectors of the linear acceleration a, the angular velocity ω and the angles ϕ are measured in the local coordinate system fixed to the 9DoF sensor and to a fixed point on the surface of the body, respectively. Starting at an initial point where the position vector r_k and the orientation matrix R_k of each sensor are well known, all values have to be calculated for each sample. First, linear velocity v^*_{k+1} and motion s^*_{k+1}, the angles α, β, γ and the local rotational matrix R^*_k are determined in the current coordinate system CS_k on the base of the known values of the sample k:

$$v^*_{k+1} = a^*_k\Delta + v^*_k \qquad s^*_{k+1} = \frac{1}{2}a^*_k\Delta^2 + v^*_k\Delta + s^*_k \tag{5}$$

$$\alpha = \omega_1\Delta, \qquad \beta = \omega_2\Delta, \qquad \gamma = \omega_3\Delta \tag{6}$$

$$R^*_k = \begin{pmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{pmatrix} \tag{7}$$

where Δ is the fixed sampling interval, k indicates the number of the sample.

Second, the resulting values are transferred to the updated coordinate system CS_{k+1} and to the inertial coordinate system CS_0:

$$R_{k+1} = R^*_k R_k \tag{8}$$

$$a_{k+1} = R^*_k a^*_{k+1} + g \tag{9}$$

$$v_{k+1} = R^*_k v^*_{k+1} \qquad s_{k+1} = R^*_k s^*_{k+1} \tag{10}$$

$$v^0_{k+1} = R_{k+1}{}^T v^*_{k+1} \qquad s^0_{k+1} = R_{k+1}{}^T s^*_{k+1} \tag{11}$$

The major disadvantage of this method consists in the accumulation of the measuring errors caused by noise or drift. After some sampling time the system has to be re-calibrated. For this purpose the data of the digital compass or other relationships (Greene, 2010; Liu, 2009) can be used. Knowing the positions and angles of joints as well as the orientation of links in the locomotor model, derived values can be determined.

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[4] http://en.wikipedia.org/wiki/Kinect

[5] http://research.microsoft.com/en-us/um/redmond/-projects/kinectsdk/default.aspx

[6] http://www.primesense.com/

[7] SHIMMER stands for 'Sensing Health with Intelligence, Modularity and Experimental Reusability

3 EXPERIMENTS AND RESULTS

Two groups of experiments were made. In both scenarios the Kinect was placed in front of the subject at the height of 88 cm and an inclination angle of 30 degree receiving the maximum area with 3 m length.

- The gait of various persons was registered simultaneously with MoCap, Kinect and SHIMMER sensors. Two cycles of each person were captured. A 9DoF SHIMMER sensor was fixed to each leg above the ankle to measure the acceleration and the angular velocity of the left and right shank. On the base of the raw data described above some gait parameters (motion of the feet, knee angle, stance phases) were calculated, not using sophisticated methods for filtering or re-calibrating data during the evaluation process.
- The gait of 32 volunteers was recorded using the Kinect sensor. Based on these data the Tinetti score (Tinetti, 1986) was calculated and the walking was evaluated comparing the measured motion of the knee with patterns given by Perry and Murray (Perry, 2010; Murray, 1964).

3.1 Comparison of MoCap and Kinect Results

All results shown in this section were taken form one collection of data selected from the test series. The intention is to compare the principle features of the three motion capture systems, not to give a statistical evaluation.

Using MoCap and Kinect sensors motion data of 23 / 20 characteristic points were captured, while the SHIMMER sensors recorded acceleration and angular velocity of both shanks. All characteristic points are located in the center of the joints of the locomotor models hidden inside the firmware. These models and following the characteristic points are different for MoCap and Kinect.

Figure 3 shows a step sequence of one test person captured simultaneously with MoCap (100 Hz) and Kinect (33 Hz). The similarity is obvious, the differences are caused in different frequencies of representation (10 to 6.7 Hz) and some effects resulting from the inclination of the Kinect sensor which are not fully compensated.

Figure 4 illustrates the motion of the left and the right foot. Regardless the small noise and the drift of the data the stance phases can be easily determined manually from the forward motion or automatically. Obviously the results meet the well-known features that the stance phases of both feet overlap or that the feet are raised during the swing phases.

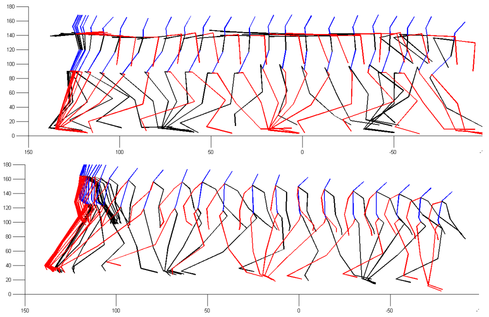

Figure 3: Motion of the subject in the skeleton view (sagittal plane): above captured with MoCap, below with Kinect; green - left, red - right extremities.

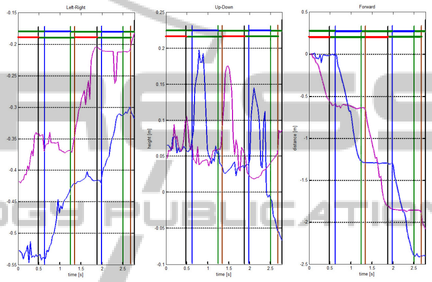

Figure 4: Motion of the left (blue) and right (pink) foot (left - left/right, center - up/down, right - forward) captured with Kinect. At the top of the plots the alternating stance (green) and swing (blue/red) phases for the left (above) and the right (below) foot are marked.

3.2 Gait Analysis using Accelerometers and Gyroscopes

As mentioned before the acceleration and angular velocity of two 9DoF SHIMMER sensors were recorded simultaneously to the MoCap and Kinect systems. Figure 5 shows the acceleration of the left and right shank in the inertial coordinate system after processing the algorithm based on the formulas (5)-(11) with compensation of the gravity force. Obviously 3 swing phases of each leg were recorded. At the same time the disruption of the x-component of the right shank and the more or less strong drift of all curves should be mentioned.

An algorithm similar to that proposed in (Greene, 2010) was applied to z-component of the angular velocity. The calculated initial and terminal contact points of the feet, are shown in Fig. 6. Peaks in acceleration (x axis) are easy to identify. Each of them represents one step of the left foot.

Figure 7 shows the motion of the left foot measured or calculated based on the data captured with the MoCap, Kinect and SHIMMER sensors. The be-

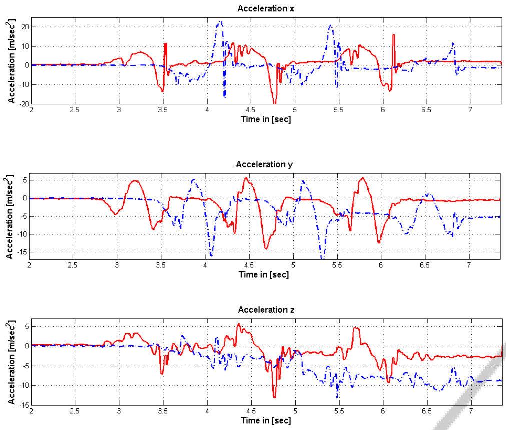

Figure 5: Accelerations of the left (blue, dotted) and right (red) shank with gravity compensated in the inertial coordinate system (x: direction of motion, y: vertical component).

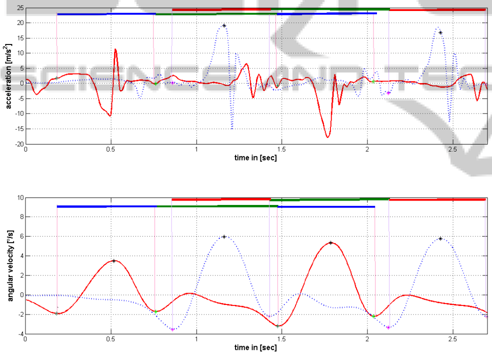

Figure 6: Acceleration x and angular velocity z of the left (blue, dotted) and right (red) shank. At the top of the plots the alternating stance (green) and swing (blue/red) phases are labeled. Initial and terminal contact points are marked with pink and green asterisks, respectively.

havior of all three curves coincide. The determination of the stance (green) and swing (blue) phases is possible. The common compromise is given in the figure. Obviously there are significant differences between the measured curves (MoCap, Kinect) and the result of the calculation (SHIMMER) applying the formulas (5)-(11).

3.3 Tinetti Score and Evaluation of Walking

Determining the Tinetti score (Tinetti, 1986) it is possible to estimate the risk of falling for elderly persons. The Tinetti test consists of a balance check and a gait analysis. A score determination of the obtained data was successful even if the scores weren't always accurate due to signal interferences. The method used for gait analysis is based mainly on the aggregation of selected parameters for the Tinetti test, as well as on the correlation of captured knee angles with patterns provided by Perry and Murray (Perry, 2010; Murray, 1964). The experimental setup where the Kinect is placed in front of the observed person permits simultaneous tracking of both body halves with one 3D-sensor. The stance and swing phases are calculated using the foot coordinates combining information of the velocity in the forward direction and the foot height over the ground. The result is shown in Fig. 8. The calculation of step length, width and height is done similarly, providing the contents of the Tinetti score.

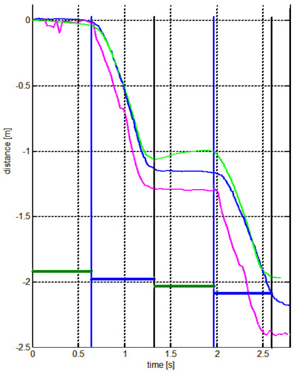

Figure 7: Motion of the left foot (blue: MoCap, red: Kinect, green: SHIMMER). Common stance (green) and swing (blue) phases are marked.

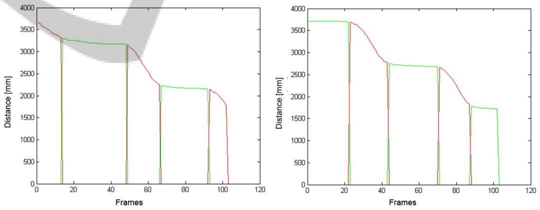

Figure 8: Stance (green) and swing (red) phases detected by the motion of the left and right foot.

The angles of the knee joints are determined using formula (4) as well as the hip, knee and foot coordinates. The quantified similarity of these angles with the standard values of Perry and Murray provides another score (correlation score).

Table 1 demonstrates the calculated values of three test persons. All records were evaluated visually (see column Q). The quality of the first record was estimated as good, while the other two were qualified as rather bad. The third had the added flaw of too much noise.

Table 2 represents the calculated Tinetti scores of the test persons with the maximum score of 5. The first two subjects achieved a very good score. Both obtained full marks from the length score and had small cuts either in the height or width score. Subject three (FH1n) only achieved the maximum score in the width. The overall score is average.

Table 1: Evaluation of three records based on Tinetti algorithm (Q = quality of record, L = step length, H_r = height right foot, H_l = height left foot, W = step width).

Name	*Q*	L $[mm]$	H_r $[mm]$	H_l $[mm]$	W $[mm]$
10442	good	613 599	42	46 50	200 165
94599	bad	736 663	55	36	131 182
FH1n	noisy, bad	15 674 558	26 80	59 116	161 148 190

Table 2: Calculated scores based on Tinetti.

Name	*Score L*	*Score H*	*Score W*	*Score total*
10442	2	2	0.5	4.5
94599	2	1.5	1	4.5
FH1n	1.67	1.25	1	3.91

The classifier based on Tinetti and correlation score was applied to 32 test subjects aged 22 to 57. More than half of the tracking sessions were affected by signal noise or a short walking range. Anyway 72% of the test persons were classified as normal.

4 CONCLUSIONS

The results of the two groups of experiments promise that both mobile sensor systems (Kinect, SHIMMER sensors) will fulfill the requirements of health applications regarding the costs and accuracy. Maybe each of them will be considered satisfactory or in some application they will be used in combination.

The investigation has shown that the accuracy of the Kinect and the SHIMMER sensors are comparable to the MoCap system. Gait cycles like stance and swing phases can be determined well.

The calibration of the setup of all three systems is very important for the quality of the measured data. Further development will be focused on the preprocessing of the raw data to eliminate the influence of noise, runaway values, offsets and drifts, on the calculation algorithms to improve differentiation/integration and to detect gait characteristics as well as to check the reliability of the systems. Adaptive procedures to recalibrate data during measurement or calculation based on correlation between e.g. acceleration and angular velocity of a foot will be investigated. The use of both sensors to special health applications like the Tinetti test will be continued.

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