Hybrid Motion Capture System for Measuring Kinematics of Vestibular Apparatus

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Abstract. This article describes the proposal of a hybrid motion capture system for studying kinematics of the vestibular apparatus. Up to now there has not been any system which would allow measuring kinematic variables of the left and right labyrinth of the vestibular apparatus in their coordinate systems by using an optical and gyro-accelerometer motion capture system. The combination of the Vicon optical system and Xsens gyro-accelerometer system allows an accurate measurement of the position and the linear and angular acceleration of the vestibular apparatus. The system was tested during the gait and head impulse test. The possible use of this system can be found particularly in the application for clinical neurology and biomechanics.

Keywords
Motion capture, vestibular apparatus, head movement, accelerometer, gyroscope

1. Introduction

The sensory system of the vestibular apparatus, which is located in the inner ear, provides a fast and precise information about the position of the head in space. Provided signals are necessary to stabilize the head and body in space and they also participate in vestibulo-ocular reflex (VOR) which stabilizes the image on the retina [1, 2].

The other sensory systems involved in the postural stability include proprioception and vision. Dysfunction of any of these systems has a significant impact on the quality of human life and increases need of medical care at general practitioners, internal medicine, ENT, neurology, orthopedics and radiology [3, 4, 5, 6, 7].

The information about the linear acceleration is provided by a pair of capsules (utriculus and sacculus). The utriculus detects the linear acceleration in the antero-posterior (boundary of the perception: 6.3 cm s⁻²) and the medio-lateral (boundary of the perception: 5.7 cm s⁻²) direction. The sacculus detects the linear acceleration in the superior-inferior direction with the boundary of the perception 15.4 cm s⁻² [8].

The information about the angular acceleration in three axes is provided by three semicircular canals, which are perpendicular to each other. The boundary of the perception differs among various studies and its value ranges between 0.37-3 deg s⁻² [9]. As the cause of this phenomenon Oosteveld considers age and psychological factors [10], stress and anxiety [11], drugs, alcohol [12] and especially various methods of measurement (standing versus sitting position) [13].

The afferent activity of ampullary nerves is mostly increased by substances containing imidazole like histamine H1, H2. On the contrary it is reduced by the antagonists of histamine H1, H2. Some types of antibiotics, like streptomycin, are ototoxic for the cochlear and vestibular function [14].

The life prevalence of the vestibular vertigo (the subjective feeling of the rotational and non-rotational movement which, due to the Earth’s system, does not occur) has a value of 7.4% (women 10.3%, men 4.3%), the annual prevalence 4.9% (women 7.1%, men 2.6%), the incidence 1.4% (women 1.9%, men 0.8%) while increasing with age. In combination with dizziness (a feeling of disturbance or disturbance of the spatial orientation without a wrong or distorted feeling of movement) the life prevalence is 29.3% (women 35.9%, men 22.6%), the annual prevalence is 22.8% (women 28.9%, men 16.7%), the incidence is 3.1% (women 4%, men 2.3%) while growing with age. It could be one of the possible causes of the injuries caused by a fall in the case of older individuals [15, 6, 16].

The benign paroxysmal positional vertigo (BPPV) is one of the most common disorders of the vestibular apparatus which may be of idiopathic or post-traumatic origin. In the study of geriatric population living in the urban center about 9% of individuals were found to have previously undiagnosed BPPV [17, 18].

Based on the magnetic resonance imaging of a group of 25 women and men, the value of the inter-utricular distance (IUD) was determined at 7.45 cm ± 0.08 cm (SE) (SD = 0.38 cm) for men and 6.99 cm ± 0.06 cm (SE) (SD = 0.32 cm) for women while it has a high correlation with the inter-mastodial distance (IMD) [12]. A simplified calculation of the IUD is shown in the equation (1).
The optimized equation utilizing the patient’s height and the distance between the nasion and the inion.

\[ IUD = 0.567 + 0.497(\text{IMD}(\text{mm})) \]  
(1)

Fig. 1 shows the position of the left and right labyrinth of the vestibular apparatus with IUD.

![Fig. 1. The position of the left (A) and right (B) labyrinth of the vestibular apparatus with IUD.](image)

The sensors organization test (SOT) using extended Romberg's test is considered as the gold standard of examination of the vestibular apparatus and other systems participating in stability [20]. The simplest test is examination of gait on a flat ground.

Head-impulse test (HIT) is one of the examination methods of the vestibular apparatus which uses VOR. HIT uses high angular acceleration (4000-6000 deg-s\(^{-2}\)) for semicircular canals examination. Examination with rotational test on the Bárány chair is used especially for utriculus examination when unilateral examination is possible [21, 22].

The aim of this article is to propose a method, which allows measuring kinematic parameters of the vestibular apparatus by using the existing commercially available systems.

2. Methods

Following systems are classified as a commercial inertial measurement systems with six degrees of freedom allowing measurement of kinematic variables of individual body segments: Xsens, InertiaCube3, 3d-Bird, 3DM-DH. These units combine 3-axis accelerometer, 3-axis gyroscope and usually 3-axis magnetometer. The accelerometers mounted on the helmet are most frequently used in evaluating the impact and the head movements in American football, hockey and football [23, 24, 25]. In some cases the mouthguard is used [26]. Danilov describes the use of the accelerometer for the electrotactile vestibular substitution [27]. In this case, the accelerometer is located on the superior side of the tongue. Differences between results provided by the accelerometers placed on helmets and those placed in the mouthpiece are examined by Higgins [28]. Handman mentions the use of the accelerometer in the earplug [29]. Cappa describes the advantage of a modified bicycle helmet with 10 biaxial accelerometers for measuring kinematic of gait parameters [30, 31]. The prosthetic reimbursement of the vestibular function comes with technological progress. This prosthetic reimbursement stimulates the afferent activity of ampullary nerves of individual semicircular canals using biphasic pulses of variable amplitude and frequency (depending on the position changes). Up to now, the system based on cochlear implant is considered as one of the most advanced systems [32].

The values measured by these accelerometers or gyro-accelerometer systems cannot be directly used as representative for the actual movement of parts of the vestibular apparatus because the position of these units is not selected with respect to the anatomical position of the vestibular apparatus, respectively left and right labyrinth.

The optical (camera) systems such as OptiTrack, Vicon and Qualysis can be also used for measuring the head position in space. Their main disadvantages are the requirements of the spatial distribution of cameras, the inability to measure large movements outside the room with cameras and the possibility of covering markers (passive/active), for example, during complex movements such as rotating on the Bárány chair.

The other motion capture (Mocap) systems use the electromagnetic field (Fastrak) or the ultrasonic signal (Zebris). Their disadvantages are the limited distance of the measurement and the fact that the measuring accuracy is negatively affected by sources of the electromagnetic field or the ultrasound sources that are commonly used in clinical practice. Due to these reasons Vicon optical system and Xsens gyro-accelerometer system were selected for the presented hybrid Mocap system.

Differences between the Vicon optical system and the Xsens gyro-accelerometer system considering measuring of the linear acceleration of upper limb during the "reach & grasp" task has been researched by Thies [33]. The design of fusion algorithm for Optical/Inertial Motion Tracking was examined by Enayati. Enayati mentions the robustness of the system in the short-loss optical marker as one of the advantages [34]. In this case, the markers of the Optotract Certus optical system were placed on ATMEL gyro-accelerometer units.

2.1 Measuring system

The measurement system is composed of the helmet with five sliding platforms allowing attachment of the Xsens gyro-accelerometer units (3-axis accelerometer, 3-axis gyroscope and 3-axes magnetometer) and the Vicon optical system reflective markers, see Fig. 2. Originally, the system was developed for measuring kinematic parameters of the vestibular apparatus during HIT and rotational test on Bárány chair with use of the Xsens gyro-accelerometer units only. The sliding plates are disposed on the helmet in a way that their planes of movement correspond with the different anatomical planes (frontal, transversal, sagittal). Sliding plates allow smooth movement in the range of 1.5 cm in all directions. The fixation is secured by locking screws. Position of the Xsens gyro-accelerometer units
with the Vicon optical system markers is defined by anatomical points on the head, according to IUD, see Eq. 1.

![Fig. 2. The helmet of the designed hybrid Mocap system: 1–sliding plate right parietal with fixed right parietal gyro-accelerometer and marker, 2–sliding plate left parietal with fixed left parietal gyro-accelerometer and marker, 3–sliding plate temporal with fixed temporal gyro-accelerometer and marker, 4–sliding plate right occipital with fixed right occipital gyro-accelerometer and marker, 5–sliding plate left occipital with fixed left occipital gyro-accelerometer and marker, 6–support structure of the helmet, 7–locking screws.](image1)

The markers of the Vicon optical system are located on the individual Xsens gyro-accelerometer unit at the position that indicates the exact position of the coordinate system in which the Xsens sensor measures. Data from the gyro-accelerometer units are transmitted by communication cables serially connected to the transmitter of the WR-A wireless communication unit from where the data are transmitted to the XbusMaster wireless communication receiver unit which is connected to the PC, see Fig. 3.

![Fig. 3. Scheme of the designed hybrid Mocap system: 1–sliding plate right parietal with fixed right parietal gyro-accelerometer and marker, 2–sliding plate left parietal with fixed left parietal gyro-accelerometer and marker, 3–sliding plate temporal with fixed temporal gyro-accelerometer and marker, 4–sliding plate right occipital with fixed right occipital gyro-accelerometer and marker, 5–sliding plate left occipital with fixed left occipital gyro-accelerometer and marker, 6–support structure of the helmet, 7–locking screws, 8–communication cable, 9–WR-A wireless communication unit.](image2)

The positions of the Vicon optical system markers are determined by seven infrared cameras which are placed with the respect to the best visibility of markers during specific movement. Data inside the cameras are preprocessed and consequently transmitted to the Vicon receiver unit through the LAN switch, see Fig. 4.

![Fig. 4. Scheme of the designed hybrid Mocap system: 6–support structure of the helmet, 8–communication cable, 9–WR-A wireless communication transmitter, 10–XbusMaster wireless communication receiver, 11–PC, 12–receiver Vicon, 13–LAN switch, 14–Vicon static camera, 15–Vicon portable camera.](image3)

### 2.2 Measurement and testing

A healthy subject (man, age 24, drug and alcohol free, without previous problem with the vestibular apparatus or stability), was selected for the testing of two types of movement. Together with the markers of the Vicon optical system the Xsens gyro-accelerometer units were set up that their axes lay on the axes of the vestibular apparatus which pass through its centre.

At the beginning of each measuring a forward bend was carried out. In order to synchronize the signals, which was manually done in the Matlab. Firstly, the measurement was performed on a subject walking without shoes on a flat ground. Secondly, the HIT was carried out by repeating rotational movements around the vertical axe of the body.

Using the Xsens gyro-accelerometer system, the inclination was measured with an accuracy of < 0.5 deg, the linear acceleration < 0.02 m s⁻² in range of ±50 m s⁻², the angular speed was measured with a precision of < 1 deg s⁻¹ in range of ±1200 deg s⁻¹, the sampling frequency was 50 Hz. The down component of the gravitational field was 9.813 m s⁻² (Kladno, Central Bohemia, Czech Republic). The west component and south component of the gravitational field were considered negligible since they were below the threshold of perception.

Position of the Vicon optical system markers were measured by using Bonita 10 cameras (resolution of 1 megapixel) with a precision < 0.5 mm. The sampling frequency was 100 Hz.
2.3 Presentation of the measured data

Since the vestibular apparatus, respectively the semicircular canals detect the angular acceleration, the numeric derivation of the angular velocity of the Xsens gyro-accelerometer units was performed using the DIFF function in Matlab. Furthermore, the conversion of rad/s² to deg/s² was performed.

The data were not filtered in any way to have the possibility of considering errors.

The resultant vector was determined for the purpose of data presentation from the linear and angular accelerations in medio-lateral (ML), antero-posterior (AP) and superior-inferior (SI) direction using the equation (2).

\[
a = \sqrt{a_{ML}^2 + a_{AP}^2 + a_{SI}^2}
\]

(2)

The resultant vectors of the linear and angular acceleration and position of the Vicon optical system markers are presented using time dependencies and the Spearman’s correlation coefficients between the kinematic data of the left and right labyrinth using the CORRCOEF function in Matlab were also calculated.

3. Results

Due to the limited article extent, the resultant vectors and positions of the right and left parietal Xsens gyro-accelerometer units and Vicon optical system markers are presented only.

3.1 Gait

In the case of the gait the value of the correlation coefficient between the resultant vectors of the linear acceleration of the right parietal (RP) and left parietal (LP) Xsens gyro-accelerometer units was 0.949, see Fig. 5. The correlation coefficient between the resultant vectors of the angular acceleration of the RP and LP Xsens gyro-accelerometer units during the gait cycle was 0.985, see Fig. 6. The positions of the RP and LP Vicon optical system markers during the gait cycle in antero-posterior (AP), medio-lateral (ML), superior-inferior (SI) direction is presented in Fig. 7.

Fig. 5. Diagram of the resultant vector of the linear acceleration of the right parietal (RP) and left parietal (LP) Xsens gyro-accelerometer units during the gait cycle.

Fig. 6. Diagram of the resultant vector of the angular acceleration of the right parietal (RP) and left parietal (LP) Xsens gyro-accelerometer units during the gait cycle.
3.2 HIT

In the case of the HIT the value of the correlation coefficient between the resultant vectors of the linear acceleration of the right parietal (RP) and left parietal (LP) Xsens gyro-accelerometer units was 0.423, see Fig. 5. The correlation coefficient between the resultant vectors of the angular acceleration of the RP and LP Xsens gyro-accelerometer units during the HIT was 0.999, see Fig. 6. The positions of the RP and LP Vicon optical system markers in anterior-posterior (AP), medio-lateral (ML), superior-inferior (SI) direction is presented in Fig. 7.
5. Conclusions

This system, unlike the other existing systems, uses the simultaneous recording of the optical system and the gyro-accelerometer, respectively the inertial system for measuring the kinematic parameters of the vestibular apparatus. This system can be used especially in clinical neurology when it allows more accurate measuring of linear and angular acceleration of the vestibular apparatus together with measuring of its position. This provides a possible comparison of the left and right labyrinth and their correlation. The future study will be focused on a possible substitution of the optical system by the gyro-accelerometer system in the case of the short-term loss of the marker visibility. As the prosthetics of the vestibular function are in the development, the more accurate measurement of the kinematic parameters of the vestibular apparatus will be required.

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Utilization of gyro

to fit in your ear.


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