Acta of Bioengineering and Biomechanics
Vol. 16, No. 2, 2014

Original paper
DOI: 10.5277/abb140210

Differences in evaluation methods of trunk sway using different MoCap systems

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The position of the trunk can be negatively influenced by many diseases. Several methods can be used for identifying defects in balance and coordination as a result of pathology of the musculoskeletal or nervous system. The aim of this article is to examine the relationship between the three methods used for analysis of trunk sway and compare two fundamentally different MoCap systems. We used a camera system and a 3DOF orientation tracker placed on subject's trunk, and measured inclination (roll) and flexion (pitch) during quiet stance. Ten healthy participants in the study were measured with eyes open and closed. The pitch versus roll plots of trunk were formed, and the area of the convex hull, area of confidence ellipse and total length of the trajectory of the pitch versus roll plot were calculated. The statistical analysis was performed and strong correlation between the area of the convex hull and area of the confidence ellipse was found. Also, the results show moderate correlation between the area of the confidence ellipse and total length of the trace, and moderate correlation between the area of the convex hull and total length of the trace. In general, the different MoCap systems show different areas and lengths but lead to the same conclusions. Statistical analysis of the participants with eyes open and eye closed did not show significant difference in the areas and total lengths of the pitch versus roll plots.

Key words: *trunk, postural stability, camera system, orientation tracker, convex hull, confidence ellipse, pitch versus roll*

1. Introduction

Currently, several methods can be used in physiotherapeutic research for identifying defects in balance and coordination. The position of the trunk can be negatively influenced by many diseases of the nervous or musculoskeletal system [1]. Subjects with peripheral vestibular deficits often show instability during stance tasks. Making the stance task more difficult by removing visual inputs has been claimed as a means to identify a vestibular deficit, evaluate the motions of stroke patients, cerebral palsy patients and normal subjects in standing [2]–[5]. The camera systems or tri-axial inertial measurement units (IMU) for orientation measurement were used for 3-D high-accuracy measurement of human body segments during quiet stance. The sensing units (in the case of inertial systems) or markers (in the case of camera system) were used to measure the pitch, roll and yaw of the segments. New techniques were introduced to quantify segment movements in both pitch (anterior–posterior) and roll (medial–lateral) directions during stance and gait tests in freely moving individuals [5]–[9]. Measurement of trunk angular movements during stance and gait tasks can detect changes in postural stability with age [6], [7], can identify impaired balance control in individuals with a vestibular deficit [5] and can track improvements in balance control over time following recovery from a vestibular deficit [10], [11]. In the studies mentioned,

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Received: August 17th, 2013
Accepted for publication: November 13th, 2013

combinations of pitch and roll sway measurements during specific balance and gait tasks identified differences in balance control of patients compared to that of healthy subjects. It is well known that the sway of standing patients with a vestibular deficit is mainly side to side (in the roll plane) and they fall to the side of the deficit [5]. Instability in other directions such as the fore-aft (pitch) plane is also seen [12]. Therefore, assessment of angular movements in the roll plane and fore-aft plane may yield clearer insights into balance deficits and provide a considerably better diagnostic tool than other more traditional measures of postural instability.

Thus, this study is aimed to use and compare 2D data about the inclination (roll) and flexion (pitch) of trunk measured by two fundamentally different MoCap systems – medical camera system with active markers and tri-axial inertial measurement unit (i.e., 3DOF orientation tracker, namely gyroscopic system). Both of these fundamentally different systems are basic MoCap systems for the study of the postural stability in 3D space. Some of the traditional methods for assessing the postural instability are methods based on the shape of the envelope (convex hull) [8], [13]–[15], 2-D confidence ellipse [16]–[18] or shape of the track of a plot [8], [19], [20], these methods are based on the description of the behavior of two variables (two angles in our case) in two human body planes/axis. Using the methods based on the shape of the convex hull, shape of the confidence ellipse of the pitch versus roll plot and total length of the trace of plot, the trunk sway measures recorded during stance tasks can provide useful information on balance deficits and disorders. Thus, the area of the convex hull, area of the confidence ellipse and total length of the trajectory of the pitch versus roll plots can be used to assess the trunk angular movements of subjects. The concepts of area of the convex hull [21], area of the confidence ellipse [22]–[24] and total length of the trajectory of the pitch versus roll plots [8], [20], although well known to the biomechanics community, have not been compared nor and the relationship between the three methods have not been examined. The results from fundamentally different MoCap systems have neither been compared used to measure trunk sway. Thus, the aim of this work is to describe relationship between the area of the convex hull, area of the confidence ellipse and total length of the trajectory of the pitch versus roll plots to determine approximate expected values of healthy individuals with eyes open or closed, and compare two fundamentally different MoCap systems/techniques used to measure trunk sway.

2. Methods and materials

2.1. Participants and test procedure

Ten healthy participants (control group – CG; age of 22.2 (SD 1.4) years) were recruited from the students at The Czech Technical University in Prague. In brief, trunk sway was measured during quiet stance. The tasks were standing on both legs on a firm surface for 60 seconds with eyes open (EO) and closed (EC). The participant's feet were positioned next to each other splayed at 30°, arms always in hanging position [25]. Each participant was measured four times with 2-min intervals between each measurement.

2.2. Motion capture equipment

One camera system with active markers and one inertial measurement unit (i.e. 3DOF orientation tracker) were used. The camera system, Lukotronic AS 200 (Lutz Mechatronic Technology e.U.) system, is widely-used medical camera system with active IR markers. Active markers were placed, in accordance with the torso portion of the upper body Plug-In Gait marker set, at the following anatomical points: 10th Thoracic Vertebrae (T10), left posterior superior iliac spine (LPSI), right posterior superior iliac spine (RPSI), [26], see Fig. 1. The MatLab software (The MathWorks Inc.) was used to identify the angles (pitch, roll) of the trunk in 3D space [27], [28]. The camera system was calibrated before the experiments, and the origin of the world coordinate system was set up so that the first axis is along the symmetry axis (coinciding with the anterior posterior axis) of the platform on which the participants stand and the other two axes are perpendicular to the symmetry axis of the platform. The sample frequency was 100 Hz.

For trunk sway measurements the motion capture system Xbus Master (Xsens Technologies B.V.) was also used which is a lightweight device with MTx units for orientation measurement of segments [29], see Fig. 1. The MTx unit is accurate 3DOF tracker. It provides drift-free 3-D orientation and 3-D acceleration. One MTx unit was placed on patient's trunk in accordance with Adkin et al. [8], Warrenburg et al. [13] and Ochi et al. [30]. The sensor was positioned at the level of the lower back (lumbar 2–3) near to the body's centre of mass without restricting movement of the hips and pelvis with respect to the trunk [8], [13], see Fig. 1. The trunk sway was measured with precision of 0.05° in three planes and the sample frequency was 100 Hz. The MT Manager software (Xsens Technologies B.V.) of the Xbus Master system was used to calculate the angles (pitch, roll) of the trunk in 3D space.

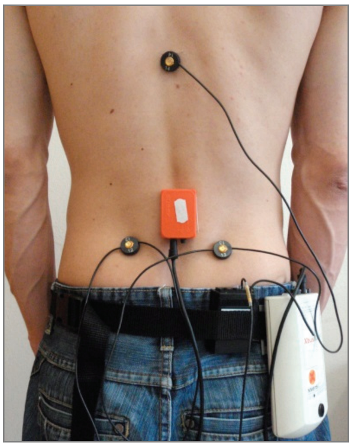

Fig. 1. Illustration of the marker set and MTx unit placed on patient's trunk

Each simultaneous measurement of one participant with EO or EC by the systems took one minute. It is not necessary to normalize the data because the standard ranges of angles are the same for the three planes of the body and all adult persons if the 3DOF orientation tracker and/or markers are placed on the same segment (i.e., anatomical points).

2.3. Methods of quantification of postural stability

After measuring the inclination (roll) and flexion (pitch) of trunk of each participant with EO or EC, the data was plotted as an *x*-*y* plot, see Fig. 2. The convex hull, confidence ellipse and total length of the trajectory were determined with the use of the MatLab software. The importance of the shape of the convex hull is well known to the biomechanics community [13]–[15]. One of the characteristics that defines the shape of the convex hull is its area. The area of the convex hull has already been used in the evaluation of the stability by force platform and center-of-pressure (CoP) displacements [21]. In our case, the area is defined by the envelope (i.e., convex hull) of the pitch and roll excursions when these variables are plotted as an *x*-*y* plot, see Fig. 2. The convex hull of a set of points in 2D space is the smallest convex region enclosing all points in the set. The convex hull computation was performed in MatLab using the Delaunay triangulation [31], [32]. Designed software based on the functions of the MatLab software calculates the area of the convex hull of the pitch versus roll plots.

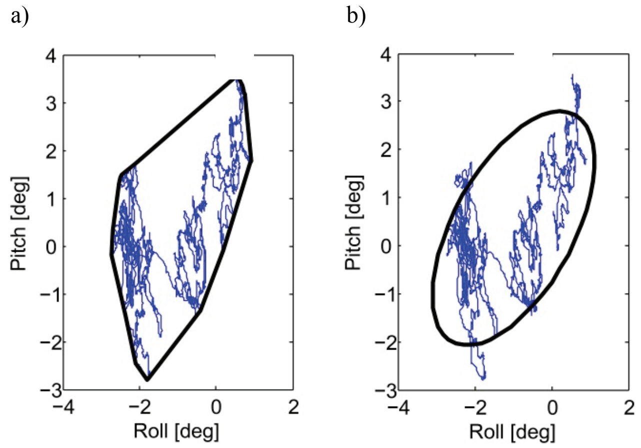

Fig. 2. Example of convex hull of a pitch versus roll plot (a) and confidence ellipse of a pitch versus roll plot of trunk (b)

Also, the importance of the area of the confidence ellipse is well known to the biomechanics community [16]–[18]. The 95% confidence ellipse area has already been used in the evaluation of the stability by force platform and CoP displacements [33], [34]. The 95% confidence ellipse area is the area of an ellipse that is expected to bound 95% of the measured data, i.e.. points on the path, Fig. 2. The 95% confidence ellipse area is given by formulas described in detail by Jørgensen et al. [33] and Prieto et al. [34]. We used software, created in MatLab software, based on the formulas described in [33], [34] to calculate the area of the convex hull of the pitch versus roll plots.

The third method to analyze the movement of trunk is based on total length of the trajectory of the pitch versus roll plots [8], [20]. The reason for the use of this method is that the standardized parameters, such as the standard deviations of displacement and planar deviation seem to be less useful because parameters appear to be independent of sampling frequency and are not correlated to any of the trajectory parameters [19], which directly reflect the measured movement of body segment. Besides, we may add that the total length of the trajectory of the plot is directly arithmetically related to mean velocity and recording time (which was the same in all our recordings) and offers similar information, provided the recording time is standardized. The total length is given by calculation described in [35]. The method of the pitch versus roll plots applied to measured data forms a trajectory, Fig. 2.

2.4. Statistical analysis

After calculating the area of the convex hull, area of the confidence ellipse and total length of the trajectory of the pitch versus roll plots of each participant with EO or EC, the statistical analysis was performed with the use of the MatLab software. First, the average values of area of the convex hull, average values of the area of the confidence ellipse and average values of the total lengths of the trajectories of the four measurements of each participant with EO and/or EC were calculated. After that, the minimum (Min), maximum (Max), median, first quartile (Q1), third quartile (Q3) and mean were calculated for the areas of the convex hulls, areas of the confidence ellipses and total lengths of the trajectories. The Jarque–Bera test was used to test the normal distribution of all parameters (significance level was 5%).

The calculated data were used to illustrate the relationship between the area of the convex hull measured by camera system (i.e., Lukotronic system) and the area of the convex hull measured by 3DOF orientation tracker (i.e., Xsens system), the relationship between the area of the confidence ellipse measured by Lukotronic system and the area of the confidence ellipse measured by Xsens system, and relationship between the total length of the trajectory measured by Lukotronic system and the total length of the trajectory measured by Xsens system. For this purpose, the Pearson product-moment correlation coefficients were calculated. Furthermore, the Pearson product-moment correlation coefficients and power trendlines were used to model the relationship between the area of convex hull, the area of confidence ellipse and the total length of the trajectory of the pitch versus roll plots.

Second, we used the descriptive statistic to illustrate the relationship between the participants (i.e., quiet stance trials) with EO and EC. The Wilcoxon signed rank test was used to assess the significance of the differences between area of confidence ellipse of the pitch versus roll plots of the participants with EO and EC, assess the significance of the differences between area of convex hull of the pitch versus roll plots of the participants with EO and EC, and assess the significance of the differences between total length of the trajectory of the participants with EO and EC. The significance level was set at $p < 0.05$.

3. Results

After calculating the areas of convex hulls, areas of confidence ellipses and total lengths of the trajectories, the statistical analysis was performed, see Table 1, Table 2 and Table 3. The charts in Fig. 3, Fig. 4 and Fig. 5 show the relationship between the area of the convex hull of the pitch versus roll plots of the participants with EO and the participants with EC, the relationship between the area of the confidence ellipse of the pitch versus roll plots of the participants with EO and the participants with EC and the relationship between the total length of the trajectory of the pitch versus roll plots of the participants with EO and the participants with EC. The Jarque–Bera test returns $h = 0$ in six cases and $h = 1$ in six cases (area of convex hull and area of confidence ellipse of the participants with EO measured by Xsens and Lukotronic system, and area of convex hull and area of confidence ellipse of the participants with EC measured by Xsens system) of measurement of the area of convex hull, area of confidence ellipse, and total length of the trajectory of the pitch versus roll plots. Since the data did not have a normal distribution, the Wilcoxon test was used to analyze the data.

Table 1. Descriptive statistics of the area of convex hull of the pitch versus roll plots of the CG with eyes open (EO) and closed (EC)

		Lukotronic CG EO	Xsens CG EO	Lukotronic CG EC	Xsens CG EC
Min	(deg^2)	0.53	2.58	0.65	2.97
Max	(deg^2)	6.44	28.58	3.90	18.08
Mean	(deg^2)	1.92	8.94	1.62	6.54
Median	(deg^2)	1.01	6.29	1.24	4.44
Q1	(deg^2)	0.72	3.24	0.81	3.24
Q3	(deg^2)	2.36	11.12	2.09	7.84

Table 2. Descriptive statistics of the area of confidence ellipse of the pitch versus roll plots of the CG with EO and EC

		Lukotronic CG EO	Xsens CG EO	Lukotronic CG EC	Xsens CG EC
Min	(deg^2)	0.76	2.94	0.85	3.42
Max	(deg^2)	11.26	50.74	5.77	28.39
Mean	(deg^2)	2.81	13.30	2.23	9.07
Median	(deg^2)	1.30	7.96	1.49	5.69
Q1	(deg^2)	0.86	4.68	1.03	4.57
Q3	(deg^2)	3.32	16.78	3.19	10.68

Table 3. Descriptive statistics of the total length of the trajectory of the pitch versus roll plots of the CG with EO and EC

		Lukotronic CG EO	Xsens CG EO	Lukotronic CG EC	Xsens CG EC
Min	(deg)	30.42	77.66	31.57	81.20
Max	(deg)	169.56	292.29	170.97	222.37
Mean	(deg)	92.27	164.61	95.13	141.70
Median	(deg)	82.16	146.27	92.13	118.81
Q1	(deg)	60.10	104.51	51.86	107.09
Q3	(deg)	128.99	220.66	133.16	195.25

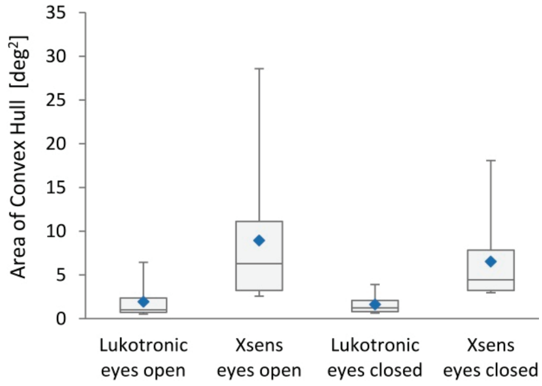

Fig. 3. Comparison of the area of convex hull of the pitch versus roll plots of the CG with EO and EC. Measured by Lukotronic and Xsens system

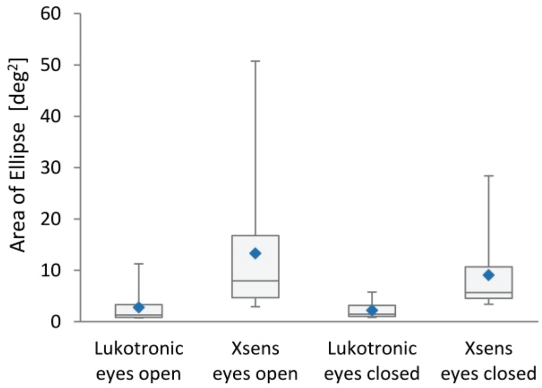

Fig. 4. Comparison of the area of confidence ellipse of the pitch versus roll plots of the CG with EO and EC. Measured by Lukotronic and Xsens system

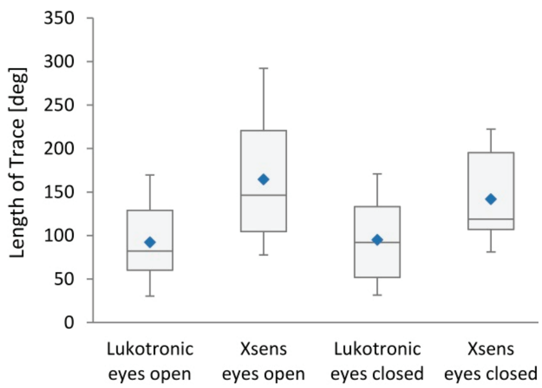

Fig. 5. Comparison of the total length of the trajectory of the pitch versus roll plots of the CG with EO and EC. Measured by Lukotronic and Xsens system

3.1. Relationship between the data measured by different MoCap systems

The Pearson product-moment correlation coefficient is 0.85 in the case of the relationship between the area of the convex hull of the participants with EO and EC measured by Lukotronic system and the area of the convex hull of the participants with EO and EC measured by Xsens system. The Pearson product-moment correlation coefficient is 0.86 in the case of the relationship between the area of the confidence ellipse of the participants with EO and EC measured by Lukotronic system and the area of the confidence ellipse of the participants with EO and EC measured by Xsens system. The Pearson product-moment correlation coefficient is 0.1 in the case of the relationship between the total length of the trajectory of the participants with EO and EC measured by Lukotronic system and the area of the total length of the trajectory of the participants with EO and EC measured by Xsens system. Correlation coefficients 0.85 and 0.86 are significantly different from zero and indicate a very strong correlation between the area of the convex hull measured by Lukotronic system and the area of the convex hull measured by Xsens system, and between the area of the confidence ellipse measured by Lukotronic system and the area of the confidence ellipse measured by Xsens system. Correlation coefficient 0.1 is close to zero and indicates a very weak correlation between the total length of the trajectory measured by Lukotronic system and the total length of the trajectory measured by Xsens system.

The median of the area of convex hull related to the participants with EO and measured by Xsens system is 6.2 times larger than the median of the area of convex hull related to the participants with EO and measured by Lukotronic system. The median of area of convex hull related to the participants with EC and measured by Xsens system is 3.6 times larger than the median of the area of convex hull related to the participants with EC and measured by Lukotronic system.

The median of the area of confidence ellipse related to the participants with EO and measured by Xsens system is 6.1 times larger than the median of the area of confidence ellipse related to the participants with EO and measured by Lukotronic system. The median of area of confidence ellipse related to the participants with EC and measured by Xsens system is 3.8 times larger than the median of the area of confidence ellipse related to the participants with EC and measured by Lukotronic system.

The median of the total length of the trajectory related to the participants with EO and measured by Xsens system is 1.8 times larger than the median of the total length of the trajectory related to the participants with EO and measured by Lukotronic system. The median of total length of the trajectory related to the participants with EC and measured by Xsens system is 1.3 times larger than the median of total length of the trajectory related to the participants with EC and measured by Lukotronic system.

3.2. Relationship between the area of convex hull and confidence ellipse

The Pearson product-moment correlation coefficient is 0.99 in the case of the relationship between the area of the convex hull and area of the confidence ellipse of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system. Also, the Pearson product-moment correlation coefficient is 0.99 in the case of the relationship between the area of the convex hull and the area of the confidence ellipse of the pitch versus roll plots of the participants with EO and EC measured by Xsens system. Correlation coefficients (0.99 in all cases) are significantly different from zero and indicate a very strong correlation between the area of the convex hull and area of the confidence ellipse of the pitch versus roll plots.

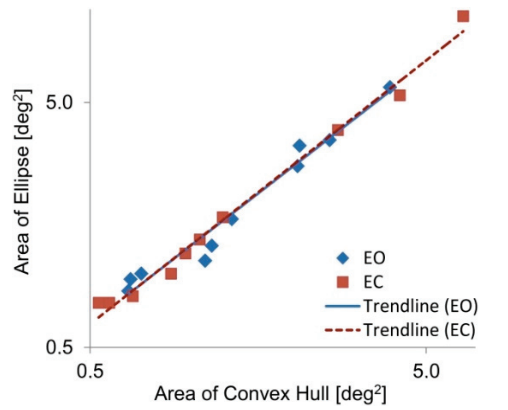

Fig. 6. Comparison of the area of convex hull and confidence ellipse of the pitch versus roll plots measured by Lukotronic system

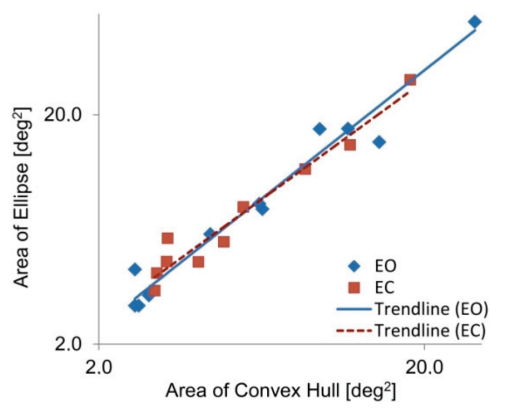

Fig. 7. Comparison of the area of convex hull and confidence ellipse of the pitch versus roll plots measured by Xsens system

The chart in Fig. 6 shows the relationship between the area of the convex hull (AH) and area of the confidence ellipse (AE) of the pitch versus roll plots measured by Lukotronic system, where the power trendline equation is $AE = 1.314 \cdot AH^{1.076}$ and coefficient of determination (i.e., squared value) is 0.99 in the case of the EO, and $AE = 1.306 \cdot AH^{1.064}$ and 0.99 in the case of the EC. Figure 7 shows the relationship between the area of the convex hull (AH) and area of the confidence ellipse (AE) of the pitch versus roll plots measured by Xsens system, where the power trendline equation is $AE = 1.094 \cdot AH^{1.119}$ and coefficient of determination is 0.97 in the case of the EO, and $AE = 1.274 \cdot AH^{1.033}$ and 0.95 in the case of the EC. The strong relationship between the area of the confidence ellipse and area of the convex hull is evident, see Fig. 6 and Fig. 7. The computational results of both methods also indicate that methods show different areas but lead to the same conclusions.

3.3. Relationship between the area of convex hull and total length of the trajectory

The Pearson product-moment correlation coefficient is 0.11 and 0.18 in the case of the relationship between the area of the convex hull and the total length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system. Also, the Pearson product-moment correlation coefficient is 0.46 and 0.65 in the case of the relationship between the area of the convex hull and the total length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Xsens system. Correlation coefficients indicate weak to moderate correlation between the area of the convex hull and the total length of the trajectory.

The following chart (Fig. 8) shows the relationship between the area of the convex hull (AH) and area of the total length of the trajectory (TL) of the pitch versus roll plots measured by Xsens system, where the power trendline equation is $AH = 0.015 \cdot TL^{1.223}$ and coefficient of determination is 0.50 in the case of the EO, and $AH = 0.440 \cdot TL^{1.112}$ and 0.44 in the case of the EC. In the case of the relationship between the area of the convex hull and the length of the trajectory of the pitch versus roll plots measured by Lukotronic system, the correlation is weak, thus the trendline is not used. The relationship between the area of the convex hull and the total length of the trajectory is weak or moderate. The computational results of both methods also indicate that methods show different results but lead approximately to the same conclusions, especially in the case of the 3DOF orientation tracker (i.e.. Xsens system).

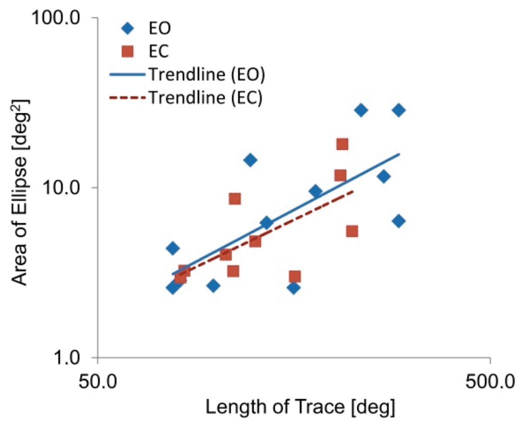

Fig. 8. Comparison of the area of convex hull and total length of the pitch versus roll plots measured by Xsens system

3.4. Relationship between the area of confidence ellipse and total length of the trajectory

The Pearson product-moment correlation coefficient is 0.20 and 0.30 in the case of the relationship between the area of the confidence ellipse and the total length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system. Also, the Pearson product-moment correlation coefficient is 0.47 and 0.62 in the case of the relationship between the area of the confidence ellipse and the total length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Xsens system. Correlation coefficients are different from zero and indicate weak to moderate correlation between the area of the confidence ellipse and the total length of the trajectory.

The chart in Fig. 9 shows the relationship between the area of the confidence ellipse (AE) and area of the total length of the trajectory (TL) of the pitch versus roll plots measured by Xsens system, where the power trendline equation is $AE = 0.006 \cdot TL^{1.462}$ and coefficient of determination is 0.55 in the case of the EO, and $AE = 0.026 \cdot TL^{1.152}$ and 0.42 in the case of the EC. In the case of the relationship between the area of the confidence ellipse and the length of the trajectory of the pitch versus roll plots measured by Lukotronic system, the correlation is weak, thus the trendline is not used. The relationship between the area of the confidence ellipse and the total length of the trajectory is weak or moderate. The computational results also indicate that methods show different results but lead approximately to the same conclusions, especially in the case of the 3DOF orientation tracker.

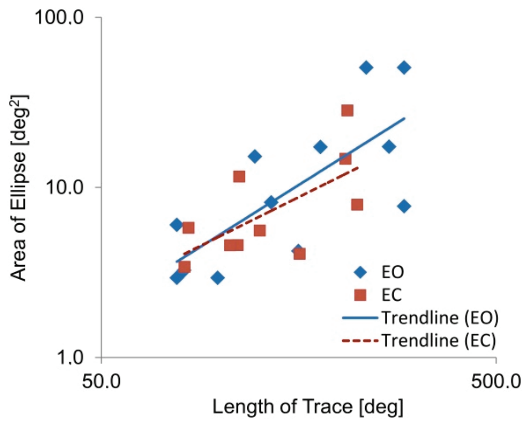

Fig. 9. Comparison of the area of confidence ellipse and total length of the pitch versus roll plots measured by Xsens system

3.5. Relationship between quiet stance trials with eyes open and closed

In the case of area of convex hull of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system, the results did not show significant difference in areas ($p = 0.94$). In the case of area of convex hull of the pitch versus roll plots of the participants with EO and EC measured by Xsens system, the results also did not show significant difference in areas ($p = 0.23$). All calculated p-values were greater than the significance level ($p < 0.05$). Therefore, we do not reject the null hypothesis, and there is no significant difference between the area of convex hull of the pitch versus roll plots of the participants with EO and EC. The median of the area of convex hull related to the participants with EC and measured by Lukotronic system is 1.23 times larger than the median of the area of convex hull related to the participants with EO and measured by Lukotronic system. The median of the area of convex hull related to the participants with EO and measured by Xsens system is 1.43 times larger than the median of the area of convex hull related to the participants with EC and measured by Xsens system.

In the case of area of confidence ellipse of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system, the results did not show significant difference in areas ($p = 0.75$). In the case of area of confidence ellipse of the pitch versus roll plots of the participants with EO and EC measured by Xsens system, the results also did not show significant difference in areas (p = 0.32). All calculated p-values were greater than the significance level ($p < 0.05$). Therefore, there is no significant difference between the area of confidence ellipse of the participants with EO and EC. The median of the area of confidence ellipse related to the participants with EC and measured by Lukotronic system is 1.12 times larger than the median of the area of confidence ellipse related to the participants with EO and measured by Lukotronic system. The median of the area of confidence ellipse related to the participants with EO and measured by Xsens system is 1.40 times larger than the median of the area of confidence ellipse related to the participants with EC and measured by Xsens system.

In the case of length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Lukotronic system, the results also did not show significant difference in areas (p = 0.32). Also, in the case of length of the trajectory of the pitch versus roll plots of the participants with EO and EC measured by Xsens system, the results also did not show significant difference in areas (p = 0.13). All calculated p-values were greater than the significance level ($p < 0.05$). Therefore, there is no significant difference between the length of the trajectory of the pitch versus roll plots of the participants with EO and EC. The median of the length of the trajectory related to the participants with EC and measured by Lukotronic system is 1.12 times larger than the median of the length of the trajectory related to the participants with EO and measured by Lukotronic system. The median of the length of the trajectory related to the participants with EO and measured by Xsens system is 1.23 times larger than the median of the length of the trajectory related to the participants with EC and measured by Xsens system.

4. Discussion

The results show strong correlation between the area of the convex hull of the pitch versus roll plot related to the participants measured by Xsens system and area of the convex hull related to the participants measured by Lukotronic system. Also, the results show strong correlation between the area of the confidence ellipse of the pitch versus roll plot related to the participants measured by Xsens system and area of the confidence ellipse related to the participants measured by Lukotronic system. However, correlation is close to zero in the case of the total lengths of the trajectories and indicates a very weak correlation between the total length of the trajectory measured by Lukotronic system and the total length of the trajectory measured by Xsens system. Nevertheless, generally, the medians of the areas and length related to the participants measured by Xsens system are higher than the medians of the areas and length related to the participants measured by Lukotronic system. The reason of different results is gyro sensor drift and skin artifacts which significantly affect the accuracy (especially in the case of 3DOF orientation tracker, which is placed on very small area, see Fig. 1). The second important reason for the phenomenon is that the MTx unit (Xsens system) detects only changes in angles at the lower trunk (lumbar 2–3), but the active markers of the Lukotronic system were placed from posterior superior iliac spine to 10th thoracic vertebrae, see Fig. 1, and therefore the values of the angles are significantly different. Therefore, the systems are not interchangeable and the same type of system must be used each time.

Interesting results are from the analysis of the relationships between the area of the convex hull, area of the confidence ellipse and the total length of the trajectory of the pitch versus roll plots. In the case of both systems (Lukotronic and Xsens system), the results show strong correlation between the area of the convex hull of the pitch versus roll plot and area of the confidence ellipse of the pitch versus roll plot. This is found in the case of participants with EO and EC. Also, the results show weak to moderate correlation between the area of the confidence ellipse and the total length of the trajectory, and between the area of the convex hull and the total length of the trajectory. A better correlation was observed in the case of using tri-axial inertial measurement unit (Xsens system). The reason for the phenomenon is that the one 3DOF orientation tracker placed on patient's trunk near to the body's centre of mass directly provides information about angles of a very small contact area of an anatomical point, and the length and areas are directly dependent on the change of the angles of a very small contact area of an anatomical point. On the contrary, the camera system detects changes in angles as a result of a complex body movement, and therefore the length of the trajectory may be different, although the size of the change of the angle can be similar to those provided by 3DOF orientation tracker. However, in general, there is moderate or high correlation independent of the type of MoCap system, and has general validity if healthy subjects are measured. The power trendline equation can be used to convert the values □□of area of the confidence ellipse, area of the convex hull and the total length of the trajectory. However, it must be considered in the calculations, the equations for the different systems are different.

It is also evident that statistical analysis (Wilcoxon signed rank test) of the participants with EO and EC did not show significant difference in the area of the confidence ellipse, area of the convex hull or total length of the trajectory. However, in the case of the use of Xsens system, the medians related to the participants with EO are slightly higher than the medians related to the participants with EC. On the contrary, in case of the use of Lukotronic system, the medians related to the participants with EC are slightly higher than the medians related to the participants with EO. The reason for the phenomenon is that the MTx unit detects changes in angles at a small area, but the active markers of the Lukotronic system detects changes in angles as a result of a complex body movement. However, in general, we can say that the different MoCap systems lead to the same conclusions, i.e., healthy CG with EO or EC did not show significant difference in the area of the confidence ellipse, area of the convex hull or total length of the trajectory.

5. Conclusions

We found that the area of the convex hull, area of the confidence ellipse and the total length of the trajectory of the trunk pitch versus trunk roll plots based on the data measured by camera system and/or 3DOF orientation tracker are suitable for study of the postural stability and could be mutually converted. Although the results are different when using different MoCap systems and evaluation methods, the MoCap systems identified the same subject's behavior. Thus, the findings also showed that a one 3DOF orientation tracker placed on patient's trunk near to the body's centre of mass could replace the complex and more expensive camera system. It is also evident that the determined values (median of areas and length, Tab. 1, Tab. 2 and Tab. 3) could be used as the expected values of healthy individuals with EO or EC during the medical examination.

The concept of area of the convex hull, area of the confidence ellipse and trajectory length, although known to the biomechanics community, has not been used before to compare the MoCap systems based on different measurement principles, and to study the relationship between the area of convex hull, area of confidence ellipse and total length of the trajectory of the trunk pitch versus trunk roll plots. The described methods can be used to compare other types of MoCap systems, and used to study angular movements of trunk, depending on the needs of a specific rehabilitation examination [36]. Methods can also be an alternative to traditional methods to study postural stability [37], [38]. The future work will be focused on the comparison of the other systems and carry out a detailed study with more participants and patients.

Acknowledgement

This work was done at FBE CTU and Charles University in the framework of research program No. VG20102015002 (2010–2015, MV0/VG), and project SGS 13/091/OHK4/1T/17 CTU Prague. The authors would like to thank Andrej Maďorán, B.A., for helping with translation of this work.

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