Journal of Equine Veterinary Science 34 (2014) 1294–1299

Contents lists available at ScienceDirect

Journal of Equine Veterinary Science

journal homepage: www.j-evs.com

Original Research

Application of a Full Body Inertial Measurement System in Dressage Riding

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ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form 8 September 2014
Accepted 14 September 2014

Keywords:
Kinematics
Inertial motion capturing
Rider
Horse
Sitting trot

ABSTRACT

With the steady further development of microelectromechanical systems, nowadays, it is possible to measure various specific kinematics of riders with inertial sensors. The aim of the study was to quantify the rider's posture on the horse with a full-body inertial measurement system (Xsens MVN) under field conditions. Ten high-level riders from the German National Equestrian Federation participated in this study. The measurements were performed in sitting trot (ST) in an indoor riding hall. Kinematic data from the riders' segments (head, trunk, and pelvis) and joint angles (elbow and knee) were collected. Qualitative analyses of the waveform parameters and statistical analyses were applied to the data. In addition, the coefficient of multiple correlations (CMCs) was calculated between angle-time courses to quantify the waveform similarities and intertrial repeatability for each rider. All analyzed CMCs ranged from moderate (0.65) to very good (0.92). The two-beat rhythm of the ST was qualitatively represented in the waveform data of the head, trunk, and pelvis about the rotation of the mediolateral axes (Roll). The Roll of the riders' pelvis was significantly greater than the Roll of the riders' trunk. In general, the movements of the riders' segments about the sagittal axes (Pitch) show smaller values than about the mediolateral axes. In conclusion, this setup seems to be suitable to quantify riders' kinematics under certain field conditions. Based on these findings, there is a possibility to obtain several objective information of the riders' kinematics in different equine gaits and skill levels.

1. Introduction

A good performance in dressage riding is mainly based on a correct rider sitting position. In BC 365, Xenophon already dealt with the question how the rider should move on a horse. Xenophon describes an upright sitting position and emphasizes the importance of a well-balanced and elastic seat of the rider [1]. These rules are still acknowledged across all equestrian disciplines down to the present day.

In the guidelines of the German National Equestrian Federation (2012), the dressage seat is defined as balanced, elastic, and upright. The requirements of a good posture are described as a vertical line between the rider's shoulder-hip-heel and a central position of the rider [2,3]. However, these theoretical considerations are difficult to grasp for researchers and horsemen [4]. It would be an improvement if more objective criteria could be developed. Biomechanical measurements could be beneficial in this matter.

At present, three-dimensional (3D) optical motion capture in gait laboratories (treadmill) is the gold standard method to quantify and analyze the rider's [5,6] and horse's movements [7–9]. Recent treadmill studies of Byström et al [5,6] and Peinen et al [10] present a comprehensive kinematic description of the rider's upper body, the saddle, and the horse trunk in walk and sitting trot (ST). However, there are differences between the locomotion of a horse on a

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http://dx.doi.org/10.1016/j.jevs.2014.09.009

treadmill and overground locomotion [11–15]. In several studies, the posture, joint angles, and kinematics of riders were investigated with camera-based measurements [16–19]. However, video-based measurement techniques show a number of disadvantages with respect to the application in horseback riding: a limited field of view, limitations concerning the acceleration measurements, and the expenditure of time and cost [20–23].

The steady development of microelectromechanical systems and inertial measurement units (IMUs) results in decreasing costs, enhanced performance, and portability [24].

The application of full-body inertial measurement systems in human movement research is becoming increasingly practicable. There are a few studies in the usage of such systems in alpine sports [25–28], clinical gait analysis [29–31], human movement research [32,33], and other sport sciences [34,35].

This new age of data capturing allows performance analyzes in horseback riding outside gait laboratories with a big sample size and high accuracy [22]. In recent years, there is a great interest in veterinary studies to collect the equine movement with IMUs [9,36–38]. The investigations of Münz et al [39,40] are one of the first who describe an inertial sensor-based method attached on rider's pelvis and horse's trunk. They found that the IMUs are suitable to collect the kinematics of human pelvis in the different equine gaits. Distinctions between the horse–rider interaction of professional riders and beginners have also been demonstrated with these methods. Wolframm et al [41] found characteristics of motor coordination between horse and rider in walk, trot, and canter based on two single triaxial wireless accelerometers. Investigations regarding the acceleration of head movement and muscular activity also point out differences depending on the gait and performance levels [42]. However, there are no publications available considering the rider's whole-body movement. It is hypothesized that a full-body kinematic analysis could contribute for a better understanding of the horse–rider interaction [20].

Hence, the aim of the current study was to evaluate the application and performance of a full-body inertial system in dressage riding and additionally to investigate the selected rider kinematics in ST.

2. Material and Methods

2.1. Riders and Horses

Ten professional dressage riders (eight females and two males; mean age ± standard deviation, 23.4 ± 5.3 years) with a body mass index of 21.5 ± 2.5 kg/m^2 and at least 17 years of experience participated in the study. All of them had worked as riding instructors at the German Federation Equestrian National (FN). The participants rode with their own dressage saddles and bits. The eight geldings and two mares (mean age ± SD: 7.9 ± 4.2 years; mean height ± SD at withers: 170 ± 3.5 cm) had been trained by the FN and did not show any sign of lameness. The experimental protocol was approved by the Ethical Board of the Otto-von-Guericke-University Magdeburg.

2.2. Experimental Design

2.2.1. Motion Capture

The kinematic data of each rider were collected with a six DOF full-body inertial measurement system (MVN; Xsens Technologies BV, Enschede, The Netherlands). The MVN consists of 17 inertial sensor modules (MTx orientation tracker; Xsens Technologies BV) and two wireless transmission units (Xbus Masters). The MTx units were attached to the riders head, hands, forearms, upper arms, shoulders, pelvis, upper and lower legs, and boots with straps (Fig. 1) and measured the position and orientation of the segments in a global coordinate system by 3D magnetometers, 3D accelerometers, and 3D rate gyroscopes [43]. Before the measurements, the MVN had to be calibrated and participants' anthropometric data (eight parameters) were raised and entered manually to a graphical user interface (Moven Studio V3.1; Xsens

Fig. 1. Experimental setup: rider (MVN suit) and horse (acceleration sensor on the cannon bone) with the applied measurement systems: rotation axes of the riders' segments are shown as arrows: red arrows indicating Roll angles and green arrows indicating Pitch angles.

Technologies BV) [44]. To obtain an accurate MVN calibration, the participants had to stand upright with their arms stretched out horizontally and the thumbs pointing forward (Xsens, standard T-Pose). All kinematic data were measured in relation to the calibrated T-Pose [43]. In accordance to the method described in Münz et al, an additional wireless 3D accelerometer (AG, RFTD-A01; Myon AG, Baar, Switzerland) was fixed onto the cannon bone of the left front limb of the horse to identify one gait cycle. The MVN (120 Hz) was synchronized with the accelerometer (120 Hz). A digital camcorder (Exilim ProEX F1 model; Casio, Tokio, Japan) was used to measure the velocity of the horse on the 30-m long sand track.

2.2.2. Procedure

After the prepared riders were introduced to the study procedure, they had time for a warm-up and to get familiar with the measuring equipment as well as the experimental setup (Fig. 1). The riders were asked to ride four times in ST straight along a 30-m sand track in the middle of an indoor riding arena. The starting and ending points of the track way were defined with clearly visible cones. During the study, the riders were instructed to ride with constant working speed on the track way.

2.2.3. Analysis

The horse's velocity was calculated for each run from the time between starting and ending points of the 30-m track. The acceleration signal of the horse's left cannon bone was zero phase-shift low-pass filtered using a recursive fourth order Butterworth filter with a cutoff frequency of 12 Hz. One single stride was defined as the time between two successive ground contacts of the left front limb. This characteristic peak could clearly be identified in the signal of the acceleration sensor. In total 30 cycles for each rider, over three trials were detected. Recorded MVN data of the rider's segment orientations (head, trunk, and pelvis), joint angles (elbow and knee), and the acceleration of the rider's trunk were exported for postprocessing and calculated with MATLAB 2012b (The MathWorks Inc, Natick, MA). Following the rules proposed by Kuipers [45], the raw global segment orientations were transformed from quaternions into Euler angles. Subsequently, the joint angles were smoothed with a moving average filter. All data were separated into strides and time normalized by using cubic spline interpolation (101 samples per stride). The joint angle of the riders' head, trunk (sternum), and pelvis were represented by rotations about two axes (Roll and Pitch). Roll describes the rotation about the mediolateral axis and Pitch about the sagittal axis. The joint angles from elbows and knees represented the rotation (flexion and/or extension) about a local axis between the proximal and distal segments.

For each measured item, the waveform similarity over 30 cycles was calculated to evaluate intertrial repeatability using the coefficient of multiple correlations (CMCs). Coefficient of multiple correlation values quantified the waveform similarity with values between 0.75 and 0.84 as good, 0.85 and 0.94 as very good, and 0.95 and 1 as excellent [46].

Table 1
Coefficient of multiple correlation (CMC) ± standard deviations of the rider's head, trunk, and pelvis around mediolateral axis (Roll) and sagittal axis (Pitch), rider's vertical acceleration (ACC), and flexion and/or extension of rider's elbow and knee over 10 subjects and 30 gait cycles.

	Mean CMC ± SD
Head	
Roll	**0.86 ± 0.15**
Pitch	0.65 ± 0.21
Trunk	
Roll	0.80 ± 0.18
Pitch	0.73 ± 0.13
ACC	**0.92 ± 0.14**
Pelvis	
Roll	**0.90 ± 0.15**
Pitch	**0.85 ± 0.10**
Elbow	
Left	0.82 ± 0.18
Right	0.81 ± 0.14
Knee	
Left	0.69 ± 0.18
Right	0.75 ± 0.15

CMCs more than 0.85 are given in bold.

Afterward, the average across 30 strides of each rider was calculated for statistical analyses. From the averaged cycles, four waveform parameters were determined: mean posture, range of motion (ROM), maximum, and minimum. The ROM of pelvis (Roll and/or Pitch) and trunk (Roll and/or Pitch) and differences between left and right elbow and left and right knee were tested for significant differences ($P \leq .05$) by using *t* test for normally distributed data and Wilcoxon signed rank test for not normally distributed.

3. Results

The mean velocity of ST was 4.4 ± 0.3 m/s^2. Across 30 gait cycles, all analyzed CMCs ranged from moderate to very good (Table 1). The highest CMC value showed the acceleration of the rider's trunk. The smallest CMC was

Table 2
Ranges of motion (ROMs), maximum (Max), minimum (Min), and mean posture ± standard deviations (SDs) of the rider's head, trunk, and pelvis around mediolateral axis (Roll) and sagittal axis (Pitch), rider's vertical acceleration (ACC), and flexion and/or extension of rider's elbow and knee over 10 subjects and 30 gait cycles.

	Mean Value ± SD			
	ROM	Max	Min	Mean Posture
Head				
Roll (°)	11.5 ± 2.9	18.8 ± 8.9	7.3 ± 8.0	14.0 ± 8.2
Pitch (°)	3.4 ± 1.9	3.9 ± 2.3	0.5 ± 1.9	2.2 ± 1.9
Trunk				
Roll (°)	7.4 ± 2.9	1.1 ± 3.9	−6.3 ± 4.4	−2.7 ± 3.8
Pitch (°)	3.1 ± 1.3	3.3 ± 2.8	0.3 ± 3.1	1.8 ± 2.9
ACC (m/s^2)	36.4 ± 8.4	25.5 ± 7.3	−10.4 ± 1.3	—
Pelvis				
Roll (°)	11.5 ± 0.9	−16.2 ± 11.1	−27.8 ± 11.4	−22.7 ± 11.4
Pitch (°)	4.0 ± 1.6	4.0 ± 3.8	0.0 ± 3.45	1.9 ± 3.5
Elbow				
Left (°)	20.5 ± 7.7	62.1 ± 9.1	41.6 ± 5.3	51.4 ± 4.9
Right (°)	16.4 ± 6.2	59.1 ± 7.5	42.7 ± 6.6	49.8 ± 6.4
Knee				
Left (°)	5.3 ± 2.2	72.4 ± 10.1	67.1 ± 9.7	69.3 ± 7.6
Right (°)	6.7 ± 2.4	70.9 ± 9.6	64.2 ± 9.9	67.8 ± 9.6

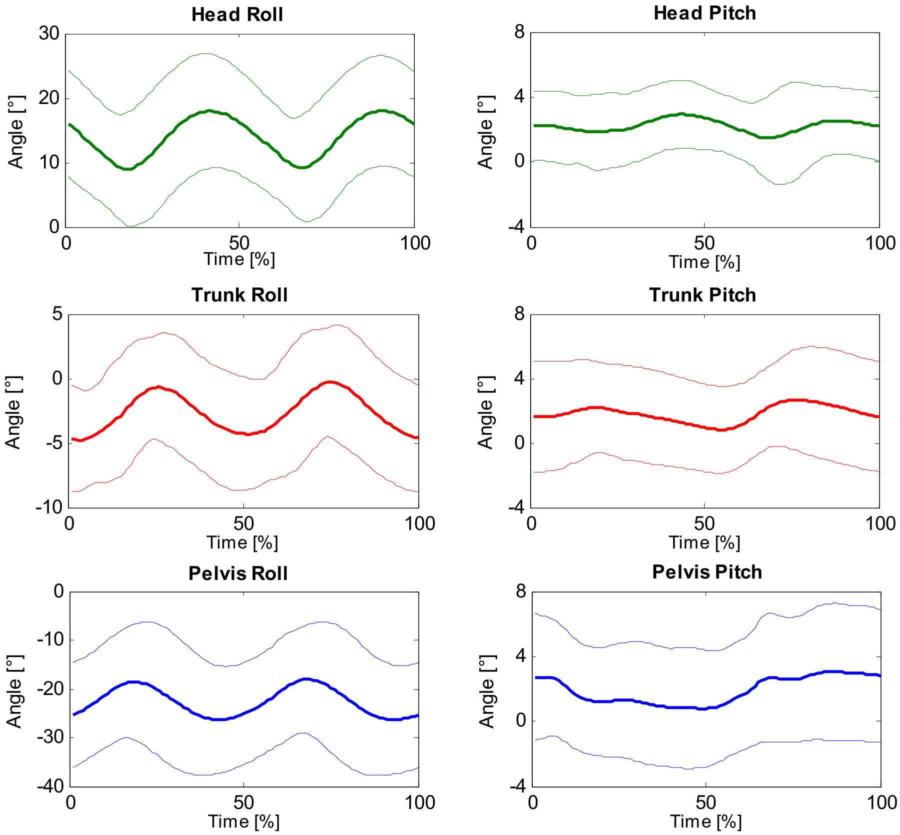

Fig. 2. Roll curves (left) represent the time-normalized group mean (solid lines) and standard deviations (dashed lines) of head (green), trunk (red), and pelvis (blue) from 10 riders about the mediolateral axis. Positive direction of Roll is to anterior (viewed from left). Pitch curves (right) represent the time-normalized group mean (solid lines) and standard deviations (dashed lines) of head (green), trunk (red), and pelvis (blue) from 10 riders about the sagittal axis. Positive direction of Pitch is to the right (viewed from behind).

found for the Pitch of the rider's head. In general, the waveform similarity of Roll was greater than the Pitch values for rider's segments. Especially for the rider's pelvis, the intertrial repeatability was very good.

It was found that the ROM values of Roll are greater than the ROM values of Pitch for all the rider's segments (Table 2). The statistical analysis showed that the ROM of rider's pelvis was significantly greater than the ROM of rider's trunk for Roll ($P \leq .01$). In other words, the pelvis tilts more than the trunk. However, the rider's pelvis tilts back with a mean posture of $-22.7° \pm 11.4°$. In comparison with the pelvis, the trunk was closer to the vertical axes with a mean posture of $-2.7° \pm 3.8°$. The rider's head tilts forward with a mean posture of $14.0° \pm 8.2°$. In Pitch, there were no significant differences among head, trunk, and pelvis in ROM. Furthermore, the ROM of the left and right knee showed a small flexion and/or extension compared with the joint angles of the elbow. All waveform parameters between left and right elbow and left and right knee indicate slight differences, which were not significant.

4. Discussion

The application of a full-body inertial measurement system is capable of estimating the rider's segment kinematics with a CMC between moderate and very good waveform similarity. In particular, the CMC values for Roll of the rider's pelvis indicate a very good intertrial repeatability. Because of the fact that horseback riding is characterized by an active and elastic seat with a high part of individualism [47], no greater CMC values for high-level dressage riders could be found in contrast to the assumption of Münz et al [39].

The velocity of the ST was similar to the velocity of the medium trot described by Clayton [48]. Particularly, the Roll-curves of head, trunk, and pelvis qualitatively represent the two-beat rhythm of ST (Fig. 2). It could be found that the riders' trunk and pelvis rotate similarly during ST. In contrast to the results of Byström et al, these findings show that the head rotated oppositely to the pelvis and trunk about the mediolateral axes. The reason for those differences could have been caused by using different measurement techniques and different biomechanical models. However, the ROM of head, trunk, and pelvis for Roll and Pitch are similar to the findings of Byström et al who published ROM values (pelvis, $13.9° \pm 2.2°$; upper body, $10.7° \pm 3.4°$; head, $15.7° \pm 4.5°$) for Roll and (pelvis, $5.1° \pm 1.1°$; upper body, $4.9° \pm 1.8°$; head, $5.9° \pm 1.1°$) for Pitch [5]. Furthermore, the calculated ROM and time series of pelvis corresponds to those of Münz et al (2013b) and emphasizes the key role for the communication between rider and horse [49]. In the phase at about of 20% and 70% of one gait cycle (moment during diagonal stance), the trunk and pelvis tilt maximal cranially and the head maximal dorsally. Throughout the hole gait cycle, the rider's pelvis (mean $\pm$ SD, $-22.7^\circ \pm 11.4^\circ$) is leant backward. These results have to be interpreted with caution because of the circumstance that all kinematic data were measured with respect to the calibrated T-Pose. Anatomic changes from a standing position to a sitting position are supposed to have taken place [50]. The mean posture of pelvis and head shows a high variability for Roll. Differences between individual riders [51] and between different riding skills [16,18,40] are published. An interindividual riding style, a different rider's body structure, and the different dressage saddles could have led to a high variability [52–54]. For Pitch, we could not find the two-beat rhythm of ST. The movements of the rider's segments about the sagittal axis displayed smaller values than about the mediolateral axis. The mean posture for head, trunk, and pelvis showed a slightly right tilt for all segments. Rider asymmetry could have been caused by the horses' anatomy or the rider's musculoskeletal system [19]. It could not be pointed out clearly why the rider's segments tilt more to the right than to the left. One possible reason could be the differences between the flexion and/or extension angles of the left and right knee during the ST, which could have had an influence in asymmetry.

In accordance to Schils et al [18], we can confirm the possibility that the knee angle is not essential to differentiate between riding skills, but they may be important for detecting asymmetries of the rider's extremities. A detailed examination of the rider's crookedness could preserve a disabled horse–rider interaction and back pain. Furthermore, the represented acceleration data of the rider's trunk (ROM, 36.4 ± 8.4 m/s^2) show a high amplitude during riding. These permanent loadings may contribute to back pain in equestrian sports.

5. Conclusions

This study demonstrated the application of a full-body inertial measurement in horseback riding under field conditions. Previous studies under field conditions have a small sample size and limited in field of view. In treadmill studies, the rider's and horse's kinematics cannot be collected under realistic conditions. To the author's best knowledge to date, there is no research with a holistic approach in horseback riding.

We have shown that this setup is suitable to quantify specific kinematics with a good intertrial repeatability. This preliminary study should describe a method to investigate the posture of high-level dressage riders in ST. Based on these comprehensible findings, it could be possible to obtain a multitude of objective information of whole-body kinematics in different equine gaits and skill levels. Especially in canter, this setup offers the possibility to assess riders' movements under realistic conditions. Future research has to investigate the kinematics of horse's trunk with an additional inertial sensor beneath the horse's sternum [39,40]. In combination with the MVN, this offers new perspectives in equine research and helps better understanding the movements of riders during horseback riding and the horse–rider interaction in different equine gaits.

Acknowledgments

We would like to thank the Federal Institute of Sport Science (BISp) for the funding of this research.

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