RESEARCH ARTICLE

Investigation of the use of inertial sensing equipment for the measurement of hip flexion and pelvic rotation in horse riders

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Abstract

Equestrian sports report three to five times higher incidence rates for lower back pain than that of the general population, with hip flexion angles of 50-60° suggested as a causal factor. Inertial motion capture technology enables dynamic measurement of rider kinematics but data extraction is time-consuming. The aim of this study was to develop a software tool to automate the process of extracting biomechanical data from the Xsens^{TM} MVN (MoCap) system to investigate postural changes in riders, comparing static position at halt with dynamic position during the sit phase of rising trot. The software was found to be efficient, reducing data extraction time by 97% when used with a sample of 16 riders. Good correlation was found between hip flexion and pelvic anterior-posterior rotation and between halt and trot but with significantly greater values of hip flexion and pelvic anterior rotation in trot. No riders showed hip flexion >50° at halt but 11 riders (69%) showed hip flexion >50° during the sit phase of rising trot, indicating that dynamic assessment is important when considering rider postural faults that may put them at risk of back injury.

Keywords: Hip flexion, Horse rider, Inertial sensor, Motion capture, Pelvic rotation

1. Introduction

Low back pain is a common musculoskeletal complaint in the general population, affecting around one-third of the UK adult population each year (National Institute for Clinical Excellence, 2009). For those who participate in equestrian sports, the incidence rate has been reported as three to five times greater than that of the general population (Pilato *et al.*, 2007).

Quinn and Bird (1996) reported that saddle type was a significant factor for the incidence rate of lower back pain, with 66% of those riding in an English-style general purpose saddle (GP) having experienced low back pain. The authors indicated the need to investigate further the link between riding posture and back pain, suggesting that in such saddles, hip extension angles of 30-40° from the horizontal (equivalent to hip flexion angles of 50-60°) are usual values. Lower back pain was reported by 70% of those who rode in a GP saddle with short stirrups compared to 59% with long stirrups but this was not found to be a statistically significant difference. However, the study was questionnaire based, using subjective responses of “long” or “short” for stirrup length rather than objective measurement, and did not take into account any postural changes of the rider during motion. This may have an impact on the angle of hip extension as the rider position alters dynamically through the different phases of the horse’s stride cycle.

Quantitative analysis of movement is more objective than qualitative analysis, allowing for comparison of data to aid evaluation and interpretation, as well as allow a way to objectively monitor technique by exploring relationships between technique and performance or injury risk (Bartlett, 2007). In the sport of cycling, it has been demonstrated that static measurements of lower limb kinematics did not coincide with dynamic measurements (Ferrer-Roca *et al.*, 2012) and significant differences have been reported in knee and ankle joint angles between static and dynamic measurements (Peveler *et al.*, 2012).

A limited number of studies have been carried out into dynamic posture of horse riders, with early studies primarily using video analysis (Bystrom *et al.* (2009); Symes and Ellis (2009); Kang *et al.* (2010)) or saddle pressure testing (Peham *et al.*, 2010). All these authors suggested the need for further studies.

The accurate three-dimensional (3D) motion capture of the human spine is a complex process, particularly in real-time, without the measurement technique interfering with the measured motion (Goodvin *et al.*, 2006). Bergmann *et al.* (2009) reported that body-worn, inertial motion sensors are a practical, non-constraining alternative to optical motion analysis. Examples of their use in research studies include analysis of hip joint flexion and extension during human walking gait (Saber-Sheikh *et al.*, 2010); assessment of spasticity assessment in children with Cerebral Palsy (Van den Noort, 2009); and measurement of lumber, hip, knee and ankle joint angles of skiers (Kondo *et al.*, 2012). Cloete and Scheffer (2008) compared inertial motion capture of human gait kinematics against optical motion capture (n=8), demonstrating good reliability for hip and knee joint angle flexion.

A preliminary study of the use of individual inertial motion sensors for rider pelvis kinematics was carried out by Münz *et al.* (2013). They analysed pelvic rotations in the anterior-posterior and lateral axes at walk, rising trot, sitting trot and canter. Results showed good within-subject repeatability of the technique but identified between-subject variability, when considering two riders on the same horse. A further study (Münz *et al.*, 2014) used individual inertial motion sensors to investigate the dynamic interaction between rider pelvis and horse, comparing professional level riders with beginners. This study reported a greater tendency towards anterior pelvic rotation in the beginner rider group in walk, sitting trot and canter gaits.

Eckardt *et al.* (2014) extended the work of Münz *et al.* (2013), using a full-body inertial measurement system (Xsens™ MVN) to capture kinematic data for the head, trunk, pelvis, elbow and knee of the rider during sitting trot. They confirmed both the within-subject repeatability and between-subject variability of the method for a larger sample size (n=10). Gandy *et al.* (2014) used the Xsens™ MVN motion capture system to measure rider hip rotation asymmetry in both straight lines and circles (12 horse and rider combinations with seven individual riders). Both studies found the technique to be efficient and practical, enabling the assessment of riders to be carried out during dynamic motion, with potential to further advance the analysis of horse and rider interactions within more realistic training and competitive environments.

Gandy *et al.* (2014) identified limitations of the technique, in the time-consuming process of manual extraction of CSV files from the XML data exported from the MVN Studio™ software, a step which was necessary to carry out statistical analysis using the R Statistical Package (R Core Team, 2015). They suggested that the development of customised software to carry out the extraction of data to CSV format would significantly reduce analysis time for future research studies and could further provide a tool for use by practitioners within the equestrian industry.

The aim of this study was to develop a software solution (using C#.Net) to reduce the time taken to parse multiple XML data files exported from MVN Studio™ for extraction of joint angle and body segment orientation data to CSV format. The resulting data was then used as input to an R script incorporating a simplistic programmatic function to determine maximum hip flexion and corresponding pelvic AP rotation values across a specified number of stride cycles for horse riders. The tool was then used to investigate the extent of postural changes in the rider, comparing static position at halt with dynamic position during the sit phase of rising trot, and to determine whether there is correlation between hip flexion angle and pelvic AP rotation.

2. Experimental

2.1 Participants

Eighteen horse and rider combinations initially presented for data collection but one was excluded for failing to meet the criteria for halt captures and one withdrew due to horse lameness. The remaining 16 combinations were included in the data analysis. The riders comprised 13 female and three male, aged 17-24 years (mean 19±2 years), with weight 52-70kg (mean 63±6 kg) and height 162-185cm (mean 172±7 cm). Riding experience ranged from 7-14 years (mean 11±2 years) and all were riding regularly at the time of data collection. The riders were self-selected volunteers, who were either students or staff members from the riding centre where data collection took place. They rode either their own horses, or horses belonging to the centre that they were familiar with.

Inclusion criteria for riders were that they were healthy, symptom free and undergoing no current treatment for back pain or musculoskeletal injury at the time of data collection. Due to the difficulty of finding participants without any history of back pain or injury, this was not used as exclusion criteria since this study was considering only the comparison between static and dynamic motion, not investigating injury effect. For this reason a convenience sample was used but this is recognised as a limitation of this study.

The horses were aged 5-20 years (mean 8±4 years), height 160-173cm (mean 166±4cm) and comprised 8 mares and 8 geldings. Breeds were 12 KWPN, one identified as simply "Dutch", one Rhineland, one Dutch/Fresian/Fjord cross and one NRPS. Inclusion criteria for horses were that they were healthy, free from disease/injury at time of data collection, in regular work and accustomed to working in different situations.

In order to maximize accuracy and quality of manoeuvres, all riders and horses were of an experience level equivalent to a minimum standard of British Dressage affiliated novice level and familiar with the activities that they were expected to perform.

All horses were ridden in their own tack, which comprised an English-style dressage saddle and stirrup length was set to the riders' normal preferred length for flatwork.

The riders were fitted with the Xsens^{TM} MVN motion capture system, comprising a full body, camera-less Lycra^{TM} suit with 17 embedded inertial measurement unit (IMU) sensors (http://www.xsens.com), incorporating accelerometers, gyroscopes and magnetometers. Data capture was set to the maximum rate of 120Hz. Prior to data collection, the suit was calibrated individually for each rider using the N-pose and T-pose calibration routines recommended by Xsens^{TM}. A detailed description of the suit and calibration method can be found in Gandy *et al.* (2014).

2.2 Data Collection

A straight runway of approximately 30m was marked out in the centre of the riding arena, using poles placed end-to-end, 1m apart. This ensured that the horse and rider combination was unaffected by the proximity of the arena's boundary wall (Gandy *et al.*, 2014).

Prior to data collection, each combination performed a brief self-selected warm-up to accustom both rider and horse to the suit and the arena layout.

A five second data capture was recorded for each combination at halt in the centre of the runway. The rider was instructed to walk the horse down the runway until the turn was completed and the horse was positioned parallel to the sides of the runway. They were instructed to execute a square, balanced halt, with the horse maintaining an even contact with the bit through both reins and remaining immobile. The rider was instructed to maintain correct riding posture and remain immobile throughout the data capture. An experienced coach observing from the ground checked that all four of the horse's metacarpal (cannon) bones were vertical and that the horse and rider remained immobile.

The combination then rode down the runway between the poles, in rising trot, on each rein (Figure 1). Data capture was started prior to the combination turning onto the runway and stopped as the rider turned out at the end.

An experienced coach observed the trials and any captures where horse or rider showed loss of balance or rhythm (or failed to remain immobile at halt) were repeated.

For halt captures, mean values across three seconds extracted from the central portion of each dataset were used in the subsequent data analysis. The original five second data captures were carried out to allow for any delayed response from the computer between pressing the record button in the software and commencement of data capture, ensuring that at least three seconds were recorded for each combination.

For trot captures, mean values across four sit phases of the stride cycle, taken from the central portion of the runway, were used in the subsequent data analysis. The number of stride cycles selected for data analysis was constrained by the size of the arena and the need to include only those strides from the centre of the runway which were not affected by the turn onto or out of the runway at the end. This is recognised as a limitation of the study and a larger arena, with longer runway, would provide more stride cycles from which mean values could be calculated. An alternative would be the use of a treadmill but this would require horses and riders to be specifically trained in the use of such equipment and it has previously been shown that the gait, speed, tempo and symmetry of the horses motion may be affected when working on a treadmill (Peham *et al.*, 2004).

Figure 1. Rider, wearing the Xsens™ MVN (MoCap) system, trotting down the marked runway.

2.3 Software Development

Datasets were exported to XML format using the MVN Studio™ software's batch export tool. A C#.Net forms-based software application was developed (using Microsoft Visual Studio 2010™) to automate the parsing of these XML files to extract joint angle and body segment orientation data. The application saved data in CSV format for subsequent analysis using the

R Statistical Package (R Core Team, 2015). A batch processing facility was incorporated to extract the required data from the large number of datasets involved. A zipfile containing a Microsoft Windows™ installer for this application is provided as electronic supplementary material (XsensConvertSetup.zip).

The application incorporates data extraction for the full 22 joint angles and 23 body segment orientations captured using the Xsens™ system, providing full flexibility for future use. For this particular study, two angles were selected for analysis: hip flexion and rotation of the pelvis about the mediolateral axis (pelvic AP rotation). Joint biomechanics used in the Xsens™ anatomical model are described in detail by Wu *et al.* (2002) and a visual representation of the relevant angles is shown in Figure 2.

Figure 2. Xsens™ anatomical measurements for hip flexion and pelvic anterior rotation. Annotated screen capture from MVN Studio™.

The automated data extraction process was tested by comparing the CSV files produced using the C# software application against those extracted manually using Microsoft Excel's XML conversion facilities, for 12 sample datasets (additional to those included in this study). The columns containing hip flexion and pelvic rotation data from the automated and manual CSV files were combined into a single spreadsheet and subtracted from each other then sorted to check for differences. After subtraction, all values were zero, indicating the CSV columns were identical and confirming that the automated process was working correctly.

Datasets for halt captures were inspected visually, using the human anatomical model avatar provided in the MVN Studio™ software, to ensure that the data frames analysed did not include any unexpected motion, for example the horse not remaining stationary or the rider showing a lack of balance. Any such artefacts were avoided when selecting frames for analysis. The MVN Studio™ software provides the facility to identify frame numbers corresponding to avatar position. Frame numbers isolating a three second portion of the data (360 frames at 120Hz) were selected and entered into a configuration file for subsequent import to a customised statistical analysis script.

Datasets for trot captures were also inspected visually, via the avatar in the MVN Studio™ software, to isolate the frames for 3 complete stride cycles. Visual inspection ensured that the stride cycles were selected for the portion of the capture where the rider was moving in a straight line through the centre of the runway and start and end frame numbers were entered into a configuration file for subsequent import to the analysis script. The selected portion of data started and ended with a sit phase of the rising trot stride cycle, ensuring that four sit-phases of the stride-cycle were included in the analysis for each combination.

A customised script was developed, using the R statistical package's proprietary scripting language, to further automate the statistical analysis process and the generation of plots. This script was designed to be easily customisable via use of configuration files, to ensure efficiency of use for multiple data files and samples requiring analysis. The R script used a parameter in the configuration file to indicate the gait captured and the method used for calculation of mean values was selected accordingly.

For halt captures, where the rider remained still, the mean value for hip flexion angle and pelvic AP rotation was calculated across all frames in the selected portion of data (3sec).

For rising trot captures, a function was included in the script to determine the mean value for hip flexion angle and pelvic AP rotation, across only the sit phase of the selected stride cycles i.e. the data point at which hip flexion angles would be at their maximum value. The source code for this function is provided in PDF format as electronic supplementary material (Document S1). The frames identified by the visual inspection provided an estimate of the start and end of the three full stride cycles, each selected at a sit phase of the stride cycle, to give four sit phases in total. Due to the rhythmical cyclic nature of hip flexion during the motion of rising trot further estimates of the intermediate stride cycle sit phases were determined by splitting this data range into three equal sized segments. Accurate values for the hip flexion at the sit phase of each stride cycle were then obtained by taking the maximum value of hip flexion in the range of frames from half a stride below to half a stride above the estimated value for each stride segment. Values were calculated separately for left and right hip to account for possible asymmetry. The pelvic AP rotation at the frame position corresponding to the maximum of the left and right hip flexion values was also determined.

Figure 3 shows the motion pattern for hip flexion (left = upper black line; right = upper grey line) and pelvic AP rotation (lower black line) for a typical rider performing rising trot. The calculated start and end positions for the seated position of the three stride cycles are indicated by solid vertical lines, with dotted lines showing the intermediate strides. For each stride the maximum values of left and right hip flexion, together with pelvic AP rotation corresponding to the seated position are marked with x. Mean values across four sit phases of the stride cycle are calculated for left and right hip flexion and pelvic AP rotation, shown on the graph as horizontal dashed lines. Such plots were used, alongside manual calculations with data values individually extracted via the MVN Studio™ software's analysis facility, with a sample of datasets to verify that the function was correctly identifying hip flexion and pelvic AP rotation values at the sit phase of each stride cycle.

Figure 3. Motion pattern of hip flexion (left = upper black line; right = upper grey line) and pelvic anterior rotation (lower black line) in rising trot. Peak hip flexion values correspond to the seated phase of the stride cycle, valleys correspond to the standing phase. Four sit phases are marked with x, mean values indicated by horizontal dashed lines.

Analysis was carried out to identify if statistical differences occur between rider posture in halt and rising trot, considering hip flexion and pelvic AP rotation angles. Further analysis was performed to determine whether correlation exists between hip flexion and pelvic AP rotation and whether any asymmetry was present in hip flexion between left and right hips.

2.4 Ethics

The project does not raise any significant ethical issues beyond the minimum standards set by the Research Ethics Committee at the Institution of the corresponding author, who has completed the institution's approved course in Research Ethics and is able to self-certify the research.

Appropriate methods of health and safety management were adopted during data collection. The horses were wearing their usual equipment, were not purposefully harmed and were considered to be carrying out their normal activities. Riders wore British Standard (BS kite marked) or European equivalent riding hats at all times when mounted. Appropriate footwear and gloves were worn both when riding and when handling the horse. The Xsens™ suit has previously been used within sporting contexts, including equestrian, so was not considered a health and safety risk. Each participant signed a disclaimer before commencing the testing. The participants have been protected by anonymity, were fully informed of the nature of the research and have given full, informed consent for the use of data collected.

2.5 Statistical Analysis

All statistical analyses were performed using the R Statistical Package (R Core Team, 2015).

The Shapiro-Wilks test was used to test whether data was normally distributed. Where this confirmed that data was normally distributed parametric methods were used, otherwise non-parametric methods were used.

Differences between recorded pelvic AP rotation and neutral pelvic orientation of zero were tested using a one-sample *t*-test. Differences between Pelvic AP rotation at halt and during the sit phase of rising trot were tested using a paired samples *t*-test. Correlation coefficients were derived, using the Pearson product moment, for the relationship between hip flexion and pelvic AP rotation and between halt and the sit phase of rising trot, for hip flexion and pelvic AP rotation.

Asymmetry values were not normally distributed so a one-sample Wilcoxon signed rank test was used to investigate asymmetry, compared to a value of zero. A paired samples Wilcoxon signed rank test was used to compare differences in asymmetry between left and right reins during the sit phase of rising trot.

For all statistical tests differences were considered significant at $P<0.05$.

3. Results

A summary of the mean values for hip flexion and pelvic AP rotation, from three seconds of halt and four sit phases of rising trot, on both left (TLR) and right (TRR) reins is provided in Table 1.

Table 1. Mean values for hip flexion and pelvic anterior rotation during three seconds of halt and four sit phases of rising trot on left and right reins.

	Left Hip Flexion (°)			Right Hip Flexion (°)			Pelvic Anterior Rotation (°)		
Horse/Rider Combination	Halt	Trot Left	Trot Right	Halt	Trot Left	Trot Right	Halt	Trot Left	Trot Right
1	46	62	62	43	65	65	6	13	13
2	25	40	51	26	44	42	-5	-1	2
3	44	63	62	41	56	58	1	6	11
4	26	49	38	35	45	54	-12	-5	-2
5	30	53	47	31	53	47	-13	3	0
6	27	49	46	27	47	47	-10	2	-1
7	26	51	38	27	44	48	-9	-5	-5
8	16	34	37	19	38	44	-19	-11	-8
9	36	64	61	48	67	71	14	21	23
10	30	48	42	26	42	48	-13	-6	-11

11	17	27	24	20	29	36	-13	-11	-8
12	22	42	48	24	46	49	-14	-6	-2
13	42	54	54	37	48	52	-4	4	3
14	42	58	52	39	62	58	1	10	9
15	33	48	44	36	50	54	4	7	11
16	25	59	55	27	54	55	-8	15	15

Mean hip flexion values at halt, for a three second data capture, ranged from 16 to 46° (mean 30±9) for the left hip and 19 to 48° (mean 32±9) for the right hip.

During the sit phase of rising trot, taking mean values across four sit phases of the stride cycle, on the left rein: left hip flexion ranged from 27 to 64° (mean 50±11) and right hip flexion ranged from 29 to 67° (mean 49±10); on the right rein: left hip flexion ranged from 24 to 62° (mean 48±10) and right hip flexion ranged from 36 to 71° (mean 52±9).

At halt, pelvic AP rotation values ranged from 19° posterior rotation to 14° anterior rotation (mean 6±9° posterior), with 11 riders (69%) having pelvic posterior rotation. This tendency towards posterior rotation was statistically significant (P=0.02).

On the left rein, mean pelvic AP rotation values for the sit phase of rising trot, taking mean values across 4 sit phases, ranged from 11° posterior rotation to 21° anterior rotation (mean 2±9° anterior). On the right rein, mean pelvic rotation ranged from 11° posterior rotation to 23° anterior rotation (mean 3±10° anterior). 9 riders (53%) on the left rein and 8 riders (50%) on the right rein showed anterior pelvic rotation but neither indicates a statistically significant tendency towards either posterior or anterior rotation (left rein P=0.32 and right rein P=0.24).

At halt, hip flexion demonstrated a significant positive correlation to pelvic AP rotation (left hip r=0.75, right hip r=0.88, both P<0.05). For the sit phase of rising trot, hip flexion demonstrated a significant positive correlation to pelvic AP rotation on both left rein (left hip r=0.84 right hip: r=0.91, both P<0.05) and right rein (left hip r=0.81, P<0.05 and right hip r=0.85, both P<0.05) (Figure 4).

Figure 4. Scatter diagrams and linear regression lines relating hip flexion to pelvic AP rotation, for mean values over three seconds of halt and four sit phases of rising trot, on left and right reins (n=16).

There was a significant positive correlation between the two gaits for hip flexion on both left rein (left hip r=0.83 and right hip r=0.86, both P<0.05) and right rein (left hip r=0.76 and right hip r=0.9, both P<0.05). There was also a significant positive correlation between halt and the sit phase of rising trot for pelvic rotation on both left rein (r=0.83, P<0.05) and right rein (r=0.88, P<0.05) (Figure 5).

Figure 5. Scatter diagrams and linear regression lines relating mean values over four sit phases of rising trot to three seconds of halt, for hip flexion and pelvic AP rotation, on left and right reins (n=16).

Statistically significant increases in both hip flexion and pelvic anterior rotation were shown between halt and the sit phase of rising trot on both left and right reins (P<0.05). Summary statistics and ranges of values for the increase in hip flexion and pelvic AP rotation values are provided in Table 2.

Table 2. Summary values across all riders (n=16) for increases in mean hip flexion and pelvic anterior rotation between three seconds of halt and four sit phases of rising trot.

	Left Rein			Right Rein		
	Left Hip Flexion (°)	Right Hip Flexion (°)	Pelvic Anterior Rotation (°)	Left Hip Flexion (°)	Right Hip Flexion (°)	Pelvic Anterior Rotation (°)
Minimum	9	10	3	7	15	2
Maximum	33	27	23	30	28	22
Mean	20	18	8	17	20	9
Standard Deviation	6	5	5	7	4	5

Summary statistics for asymmetry between left and right hip flexion, are provided in Table 3. Data were not normally distributed so a paired samples Wilcoxon signed rank test was used to test for statistical significance. In both halt and the sit phase of rising trot, the presence of asymmetry between left and right hip flexion (taking absolute difference values) was found to be statistically significant for halt and the sit phase of rising trot on both reins ($P<0.05$). The maximum asymmetry recorded for individual riders was 12° for halt, 8° for trot on the left rein and 16° for trot on the right rein, in each case for different riders. However, across the full sample (n=16) there was no statistically significant difference in asymmetry measured between trot on the right and left reins ($P=0.21$).

When considering the direction of the asymmetry, a paired samples Wilcoxon signed rank test showed that there was no significant bias towards greater flexion of either the left or right hip in halt. However, there was a statistically significant difference between directional asymmetry in trot between the left and right reins ($P<0.05$), with no significant bias towards greater flexion of left or right hip on the left rein but a statistically significant bias towards greater flexion of the right hip on the right rein (*P*-values are included in Table 3).

Table 3. Summary data across all riders (n=16) for asymmetry in mean hip flexion during three seconds of halt and four sit phases of rising trot.

	Absolute Asymmetry			Directional Asymmetry (left hip flexion – right hip flexion)		
	Halt (°)	Trot Left (°)	Trot Right (°)	Halt (°)	Trot Left (°)	Trot Right (°)
Range	0 to 12	0 to 8	0 to 16	-12 to 5	-5 to 8	-16 to 9
Interquartile Range	2 to 4	3 to 5	2 to 10	-3 to 3	-4 to 5	-10 to 0
Median	3	4	6	-1	-1	-5
P-value	<0.05	<0.05	<0.05	0.6	0.52	<0.05

The MVN Studio™ software supplied with the Xsens™ suit provides a 3-dimensional representation of the data using a human anatomical model. Figure 6 shows a pair of screen captures from MVN Studio™, for a sample rider (horse/rider combination 16), comparing halt with the sit phase of rising trot. Greater hip flexion values and increased anterior rotation of the pelvis in the sit phase of the trot can be clearly seen.

Figure 6. Comparison between halt (left image) and the sit phase of rising trot (right image). Screen capture from MVN Studio™.

Figure 7 shows the range of pelvic AP rotation across the full data sample for halt and the sit phase of rising trot, i.e. sample screen captures from MVN Studio™ for the two riders with the most posteriorly and anteriorly rotated pelvis at halt and the two riders with the most posteriorly and anteriorly rotated pelvis during the sit phase of rising trot.

Figure 7. Range of pelvic anterior-posterior rotation across the full data sample. Screen capture from MVN Studio™.

4. Discussion

The aim of this study was to develop a C#.Net software application to automate the process of parsing XML data files exported from MVN Studio™, to extract joint angle and body segment orientation to CSV format for ease of input to statistical analysis packages such as R. This has previously been identified as a limitation to the practical use of the technology for rider analysis due to the time consuming process of manual extraction of data via Excel, reported as approximately 90 seconds per dataset (Gandy *et al.*, 2014). The data sample analysed in this study required the extraction of data files for 16 riders x three gait variations (halt, trot left, trot right) x two anatomical measures (joint angles, body segment orientation), amounting to a total of 96 datasets. Assuming 90 seconds per dataset, the time required to extract the data manually can be estimated as 144 min. Processing this quantity of data manually would also introduce the risk of errors, due to the repetitive nature of the task. The development of the C#.Net automated batch extraction software reduced the time taken to generate the 96 CSV files required for analysis by 97%, to less than 5 min. The forms-based interface provided within this software was designed to be intuitive in order to provide a tool for use by researchers, without the need for specific training. It has subsequently been used within the authors' institution, both for research and teaching purposes.

The R script developed for the data analysis phase was designed to be flexible, using customisable configuration files which provide the parameters for a series of functions. This will enable it to be utilised with minimal modification in future projects, both in equestrian and other fields. The script also incorporates a simplistic programmatic function for calculating maximum hip flexion and corresponding pelvic AP rotation values, across a range of stride cycles identified via manual inspection of the data within the Xsens system's proprietary software MVN Studio, with a parameter to specify the number of stride cycles. The source code for this function is provided as electronic supplementary material (Document S1). For this study, only four sit phases of the stride cycle were identified for each dataset, a constraint of the riding arena size, but the function has also been tested with a cyclist mounted on a static bike (Gandy and Pigott, unpublished data), accurately identifying maximum hip flexion values across 70 pedal revolutions.

A further aim of the study was utilise the software developed to compare hip flexion and pelvic AP rotation between halt and the sit phase of rising trot, in order to investigate the potential for its use for dynamic postural analysis of horse riders using inertial motion sensor technology.

The posture of the rider whilst seated at halt was compared with their posture during the seated phase of rising trot as an indicator of the rider's dynamic balance. Rising trot is characterised by a temporary loss of contact between the saddle and the rider's pelvis during the rise phase of each stride (Münz *et al.*, 2013). The rider's pelvis is the centre of movement that determines the coordination between upper body and legs and plays the key role in controlling the horse by physically connecting the rider's body weight (via the saddle) with the horse (Münz *et al.*, 2013). Thus, a seat fault in the pelvis may result in a problem somewhere else in the rider's body (Blokhuis *et al.*, 2008).

The transition from the rise phase to the seated phase of rising trot requires a coordinated shift in balance from the rider's foot, positioned in the stirrup, to the seat bones in the saddle, whilst in synchronisation with the stride cycle of the horse. This movement requires skilled riding technique to achieve harmony so any lack of balance and/or coordination will become more evident. It was, therefore, hypothesised that a seat fault at halt would be emphasised during the seated phase of rising trot and this study found a positive correlation between the two seated postures, with significant increases in hip flexion and pelvic anterior rotation.

Finely-tuned coordination of the spinal muscles are necessary to maintain optimal control of dynamic intervertebral, spinal and postural stability while enabling the desired flexibility of movement to be carried out (Reeves *et al.*, 2007). In the context of horse riding, dynamic motor control involves interplay between feedback and feedforward control mechanisms to modulate muscle activity to control the changing internal forces and external forces from the horse's movements. Classic riding posture has shown hip angles of 30 to 40° to the horizontal (equivalent to hip flexion angles of 50-60°), causing flattening of the lumbar lordosis, placing stress on the lumbar spine, involving up to 65% of the individual's body weight (Quinn and Bird, 1996).

Of the 16 combinations analysed in this study, no riders showed hip flexion angles greater than 50° at halt; however, 11 riders (69%) showed hip flexion angles greater than 50° for one or both hips on either or both reins during the sit phase of the rising trot cycle on a straight line, with a mean increase of 19° when combining left and right hips on each rein. This indicates that the rider fails to control the lumbar-pelvic-hip complex during motion, resulting in increased anterior pelvic rotation, with a mean increase of 9° recorded for this sample of riders, when combining left and right rein data. This indicates that simply measuring the rider's stirrup length or postural alignment at halt is insufficient; it is necessary to consider dynamic posture to provide a more reliable indication of whether they fall within the Quinn and Bird (1996) risk indicator for potential back injury of hip flexion values greater than 50°.

Quinn and Bird (1996) suggest that longer stirrup lengths, with hip angles of 45° to the horizontal, maintain the neutral lumbar lordosis which will naturally absorb the compression forces of the riding action. However, the increased pelvic anterior rotation found in this study indicates that measuring the hip angle to the horizontal may result in an under-estimation of the true hip flexion, since this measure presumes that the rider's pelvis is in neutral alignment.

Good correlation was found between hip flexion and pelvic AP rotation and between halt and the sit phase of rising trot; however, values for both hip flexion and pelvic AP rotation varied greatly between subjects in both halt and the sit phase of rising trot. These findings support and expand on studies by Münz *et al.* (2014), who identified significant inter-subject variations in pelvic AP rotation at walk, sitting trot and canter, based on data from a single

IMU placed on the rider pelvis and Eckardt *et al.* (2014), who further confirmed and extended the findings for a range of anatomical measures (including pelvic AP rotation) at sitting trot.

Previous studies investigating asymmetry in rider hip flexion (Clayton, 2013), knee flexion (Eckardt *et al.*, 2014) and hip external rotation (Gandy *et al.*, 2014) have reported a significant bias in directional asymmetry to the right. In this study, asymmetry in hip flexion was observed at all gaits but with variation according to which rein they were on. Significantly greater flexion of the right hip on the right rein was identified, supporting the findings of Clayton (2013) but no bias towards left or right hip on the left rein. The riders were asked to identify left or right dominance of hands and feet but, unlike the findings reported in Clayton (2013), this was not found to have a statistically significant effect on the hip flexion asymmetry values. Comparing asymmetry across studies is difficult due to the differences in gait and joint angles being measured; however, there does appear to be a general bias towards directional asymmetry to the right.

A limitation of this study was that asymmetry in the gait of the horse was not measured, which could be affecting the rider's motion patterns. Due to the small sample sizes of all studies to-date, further research is necessary to identify whether the right bias is a general pattern and if asymmetry in hip flexion and other joint angles is caused by rider or horse asymmetry. Riders were asked to complete a questionnaire which included history of back pain and injury, to which nine riders responded positively (56%). Whilst this figure was broadly comparable with the findings of Quinn and Bird (1996), no significant correlation was found between this group and those with greater hip flexion or pelvic anterior rotation. A larger sample size and more detailed analysis of back pain and injury history would be necessary before any reliable conclusions could be drawn on causal links between rider posture and back pain or injury.

It is recognised that it is difficult to achieve a correct balanced halt and several repetitions were required from most combinations to achieve the specified criteria for an acceptable data capture. It is a limitation of the study that subjective observation was used to determine whether combinations met the criteria and it is suggested that further development of the tool could include machine learning techniques to automate gait recognition and determine consistency of data captured. In this study, one combination was excluded from the analysis due to failure to achieve the required criteria for halt captures.

Due to limitations in the number of stride cycles available for analysis in this study, mean values have been used for hip flexion and pelvic AP rotation but further work is necessary, using a larger sample size and increased number of stride cycles, to measure variability within horse and rider combinations. There is also a need for validation studies to confirm the repeatability and reliability of the technique and comparability with other methods e.g. video analysis.

Further research, using a significantly larger sample size, would be required to determine guideline ranges for hip flexion and pelvic AP rotation angles to reduce risk of injury to the hip and lumbar spine.

5. Conclusion

This study has demonstrated that the use of inertial motion sensing technology, such as that provided by the Xsens^{TM} motion capture suit, can be used to measure hip flexion and pelvic

AP rotation during riding motion. The data conversion software developed to export the data in a format suitable for input to statistical analysis packages was found to be efficient, significantly speeding up the data preparation process by reducing the time taken per dataset from 90 seconds to just over 3 seconds.

The correlation between hip flexion angle and pelvic AP rotation demonstrates that measuring the angle of the hip to the horizontal is insufficient for accurate rider postural assessment. It cannot be assumed that riders will be sitting in a neutral posture so the orientation of the pelvis should be taken into account when considering hip flexion. The increase in hip flexion and pelvic anterior rotation identified between halt and the sit phase of the rising trot indicates that it is necessary to consider dynamic posture when assessing riders. The presence of asymmetry in hip flexion at both halt and trot also requires consideration, as this may be a further risk factor for potential injury. In addition, variations in asymmetry between left and right directions indicate that it is vital to ensure analysis is carried out on both reins both in practical rider assessment contexts and in research studies.

The system developed has the potential for use in a practical context to provide biofeedback to rider and coach, after completion of a riding session with the rider wearing the motion capture technology. By assessing riders' movement control using such technology, it may be possible to identify those riders who are unstable in trot in order to target coaching cues and implement corrective exercise programs. Further research is required to confirm whether hip flexion angles of more than 50° are a causal factor for lower back injury and establish whether, through feedback and corrective exercises, the lumbar-pelvic-hip control can be improved in horse riders.

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Conflict of Interest

All contributing authors declare that they have no financial and/or personal relationships with other people or organisations that could inappropriately influence this work.

References

Bartlett, R., 2007. Introduction to Sports Biomechanics: Analysing Human Movement Patterns. Routledge.

Bergmann, J.H., Mayagoitia, R.E. and Smith, I.C., 2009. A portable system for collecting anatomical joint angles during stair ascent: a comparison with an optical tracking device. Dyn Med 8: 1-7.

Blokhuis, M.Z., Aronsson, A., Hartmann, E., Van Reenen, C.G. and Keeling, L., 2008. Assessing the rider's seat and horse's behavior: difficulties and perspectives. J Appl Anim Welf Sci 11: 191-203.

Bystrom, A., Rhodin, M., von Peinen, K., Weishaupt, M.A. and Roepstorff, L., 2009. Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. Equine Vet J 41: 280-284.

Clayton, H.M., 2013. Science in brief: Interactions between the rider, the saddle and the horse. Equine Vet J 45: 3-4.

Cloete, T. and Scheffer, C., 2008. Benchmarking of a full-body inertial motion capture system for clinical gait analysis. Conf Proc IEEE Eng Med Biol Soc 2008: 4579-4582.

Eckardt, F., Münz, A. and Witte, K., 2014. Application of a Full Body Inertial Measurement System in Dressage Riding. Journal of Equine Veterinary Science 34: 1294-1299.

Ferrer-Roca, V., Roig, A., Galilea, P. and Garcia-Lopez, J., 2012. Influence of saddle height on lower limb kinematics in well-trained cyclists: static vs. dynamic evaluation in bike fitting. J Strength Cond Res 26: 3025-3029.

Gandy, E.A., Bondi, A., Hogg, R. and Pigott, T.M.C., 2014. A preliminary investigation of the use of inertial sensing technology for the measurement of hip rotation asymmetry in horse riders. Sports Technology 7: 79-88.

Goodvin, C., Park, E.J., Huang, K. and Sakaki, K., 2006. Development of a real-time three-dimensional spinal motion measurement system for clinical practice. Med Biol Eng Comput 44: 1061-1075.

Kang, O.D., Ryu, Y.C., Ryew, C.C., Oh, W.Y., Lee, C.E. and Kang, M.S., 2010. Comparative analyses of rider position according to skill levels during walk and trot in Jeju horse. Hum Mov Sci 29: 956-963.

Kondo, A., Doki, H. and Hirose, K., 2012. An attempt of a new motion measurement method for alpine ski turns using inertial sensors. Procedia Engineering 34: 421-426.

Münz, A., Eckardt, F., Heipertz-Hengst, C., Peham, C. and Witte, K., 2013. A Preliminary Study of an Inertial Sensor-based Method for the Assessment of Human Pelvis Kinematics in Dressage Riding. Journal of Equine Veterinary Science 33: 950-955.

Münz, A., Eckardt, F. and Witte, K., 2014. Horse-rider interaction in dressage riding. Hum Mov Sci 33: 227-237.

National Institute for Clinical Excellence, 2009. CG88 Low back pain: Early management of persistent non-specific low back pain.

Peham, C., Kotschwar, A.B., Borkenhagen, B., Kuhnke, S., Molsner, J. and Baltacis, A., 2010. A comparison of forces acting on the horse's back and the stability of the rider's seat in different positions at the trot. Vet J 184: 56-59.

Peham, C., Licka, T., Schobesberger, H. and Meschan, E., 2004. Influence of the rider on the variability of the equine gait. Hum Mov Sci 23: 663-671.

Peveler, W.W., Shew, B., Johnson, S. and Palmer, T.G., 2012. A kinematic comparison of alterations to knee and ankle angles from resting measures to active pedaling during a graded exercise protocol. J Strength Cond Res 26: 3004-3009.

Pilato, M.L., Shifrin, S. and Bixby-Hammett, D., 2007. The equestrian as an athlete: A view into injuries and incidence rates. Equestrian Medical Safety Association Newsletter: 5-7.

Quinn, S. and Bird, S., 1996. Influence of saddle type upon the incidence of lower back pain in equestrian riders. Br J Sports Med 30: 140-144.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.

Reeves, N.P., Narendra, K.S. and Cholewicki, J., 2007. Spine stability: the six blind men and the elephant. Clin Biomech (Bristol, Avon) 22: 266-274.

Saber-Sheikh, K., Bryant, E.C., Glazzard, C., Hamel, A. and Lee, R.Y., 2010. Feasibility of using inertial sensors to assess human movement. Man Ther 15: 122-125.

Symes, D. and Ellis, R., 2009. A preliminary study into rider asymmetry within equitation. Vet J 181: 34-37.

Van den Noort, J., Scholtes, V. and Harlaar, J., 2009. Evaluation of clinical spasticity in cerebral palsy using inertial sensors. Gait and posture 30: 138-143.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I., Standardization and Terminology Committee of the International Society of, B., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion--part I: ankle, hip, and spine. International Society of Biomechanics. J Biomech 35: 543-548.

Figures

Figure 1.
Rider, wearing the Xsens^{TM} MVN (MoCap) system, trotting down the marked runway.

Figure 2.
Xsens^{TM} anatomical measurements for hip flexion and pelvic anterior rotation. Annotated screen capture from MVN Studio^{TM}.

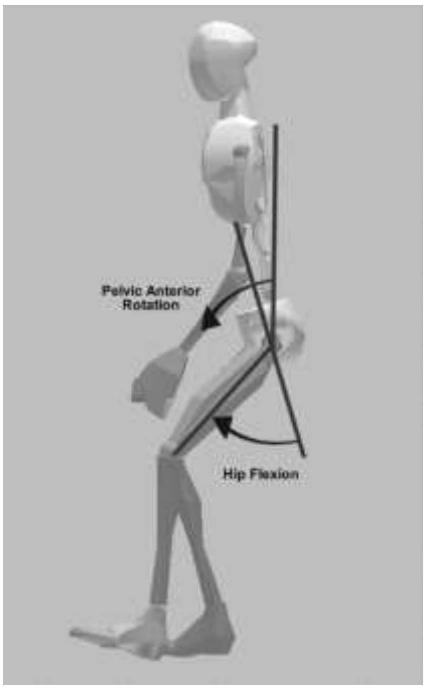

Figure 3.
Motion pattern of hip flexion (left = upper black line; right = upper grey line) and pelvic anterior rotation (lower black line) in rising trot. Peak hip flexion values correspond to the seated phase of the stride cycle, valleys correspond to the standing phase. Four sit phases are marked with x, mean values indicated by horizontal dashed lines.

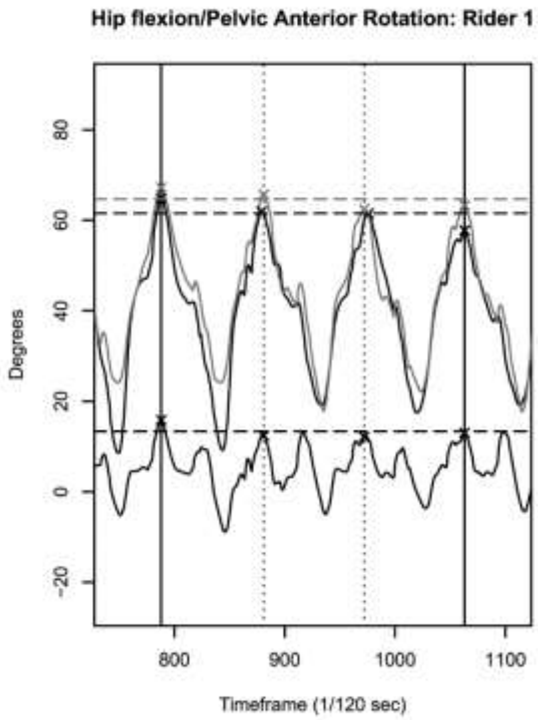

Figure 4.
Scatter diagrams and linear regression lines relating hip flexion to pelvic AP rotation, for mean values over three seconds of halt and four sit phases of rising trot, on left and right reins (n=16).

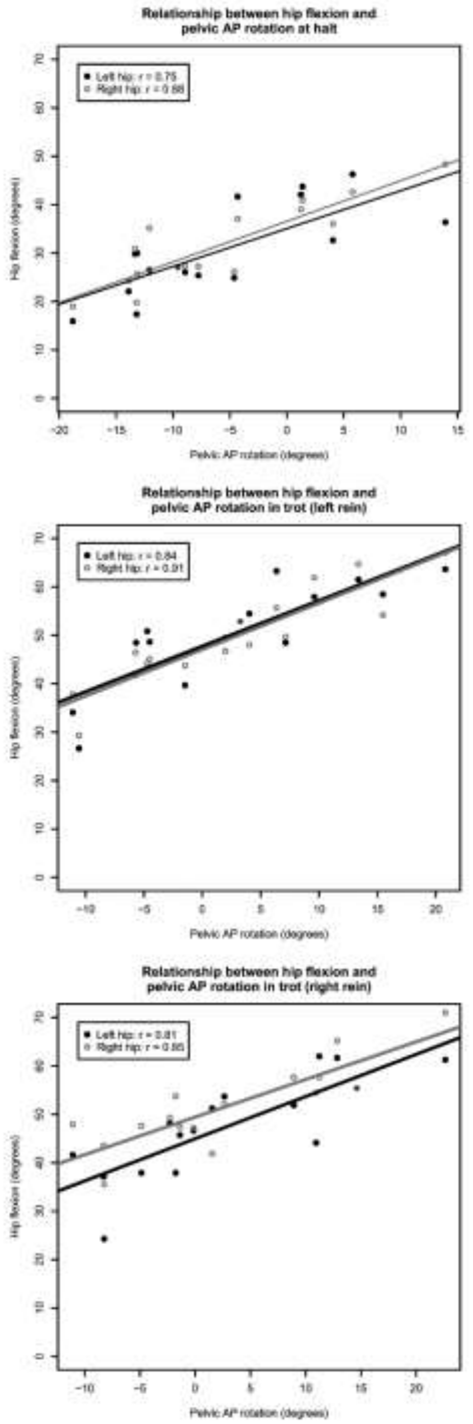

Figure 5.
Scatter diagrams and linear regression lines relating mean values over four sit phases of rising trot to three seconds of halt, for hip flexion and pelvic AP rotation, on left and right reins (n=16).

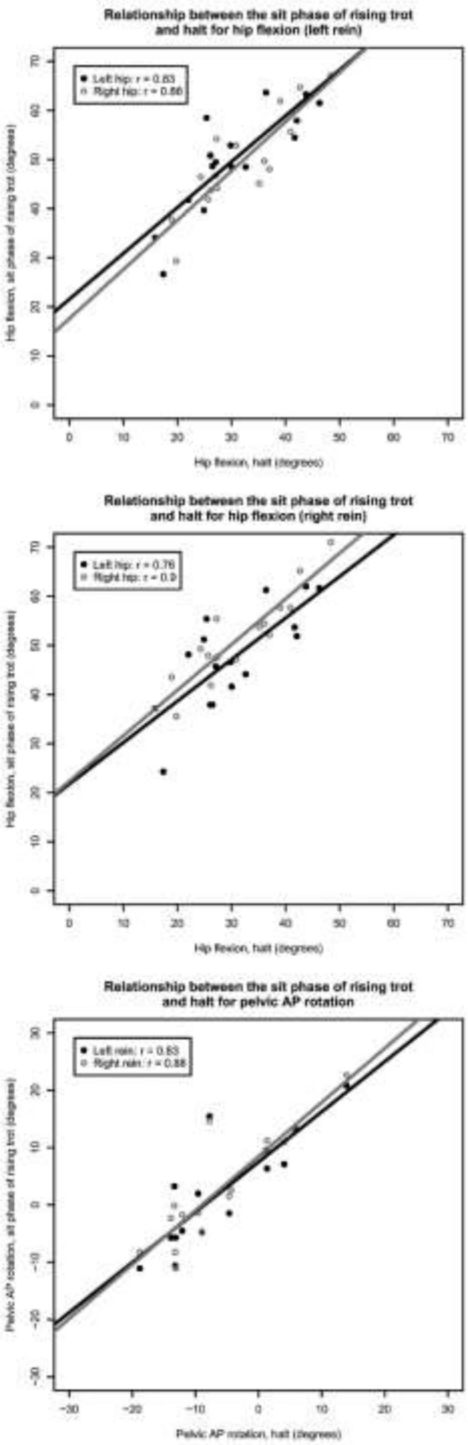

Figure 6.
Comparison between halt (left image) and the sit phase of rising trot (right image). Screen capture from MVN Studio™.

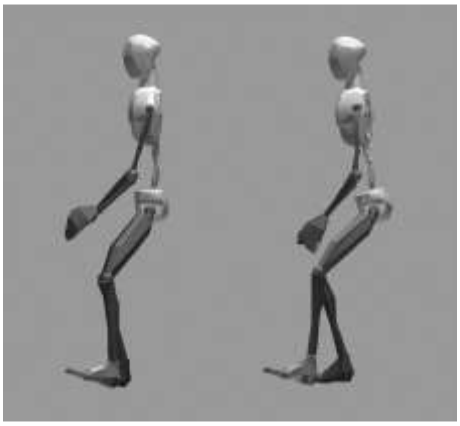

Figure 7.
Range of pelvic anterior-posterior rotation across the full data sample. Screen capture from MVN Studio^{TM}.