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A sphere fitting approach to determine the hip joint centre of the horse

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Running header: Hip joint centre in the horse

Abstract

Accurate identification of the hip joint centre (HJC) is crucial for the correct estimation of knee and hip joint loads and kinematics, which is particularly relevant in orthopaedic surgery and musculoskeletal modeling. Several methods have been described for calculation of the HJC in humans, however, no studies have used these methods in the horse despite a similar need for improved evaluation of hip joint biomechanics in rehabilitation and musculoskeletal modeling. This preliminary study uses the commonly used functional method (least-squares sphere fit) to determine the HJC in three equid cadavers. Bone pins with reflective markers attached were drilled into the tuber coxae (TC), tuber ischium (TI), tuber sacrale (TS), greater trochanter (GT), third trochanter (TT) and lateral femoral condyle (FC) of the uppermost limb of the cadavers positioned in lateral recumbency. Three repetitions of passive movements consisting of pro-and retraction, ab- and adduction and circumduction were performed. The HJC was calculated using a least-squares sphere fitting method and presented as a distance from the TC based on a percentage of the TC to TI vector magnitude. Mean (± standard deviation) of the HJC is located 52.4% (± 3.9) caudally, 0.2% (± 6.5) dorsally, and 19.8% (± 4.2) medially from the TC. This study is the first to quantify the HJC in horses *in vitro* using a functional method. Further work (*in vitro*, *in vivo* and imaging) is required to validate the findings of the present study.

Keywords:

Equine, Ex vivo, Biomechanics, Kinematics

Introduction

Identification of the hip joint centre (HJC) is important for the estimation of hip joint kinematics and moments (Cereatti *et al.*, 2009, Ehrig *et al.*, 2006) and for the optimisation of implant placement in hip and knee surgery (Boudroit *et al.*, 2006). Although there is a wealth of literature available on the HJC in man, to our knowledge, the HJC has not been quantified in horses. Identifying the HJC in horses is mandatory for musculoskeletal modelling purposes. In addition, it can improve the evaluation of pelvic limb kinematics in pathology such as hip (sub)luxation (Barr and Fairburn, 2014) and osteoarthritis (Lamb and Morris, 1987).

Functional and predictive methods have been used to identify the HJC in man (Camomilla *et al.*, 2006). Predictive methods are based on regression equations and anthropometric measurements (Fiorentino *et al.*, 2015) or medical imaging (De Momi *et al.*, 2009). The functional method assumes a spherical ball and socket joint with the geometric centre of the acetabulum representing the centre of rotation of the hip joint; this is quantified by tracking movement of the femur relative to the pelvis (Camomilla *et al.*, 2006). Several algorithms based on sphere-fitting have been used for the functional approach in man (e.g. Gamage and Lasenby, 2002, Piazza *et al.*, 2001), with good accuracy and repeatability (Camomilla *et al.*, 2006; Ehrig *et al.*, 2006).

Although the functional method is more accurate than the predictive method (Fiorentino *et al.*, 2015, Hicks and Richards, 2005), it is nonetheless prone to errors from skin and soft tissue displacement when skin markers are used (Cereatti *et al.*, 2009). While skin displacement of 5mm over the greater trochanter in the direction perpendicular to the long axis of the femur has been reported in man during walking (Leardini *et al.*, 2005), in horses over the same location and direction, skin displacement of 142mm has been identified during trot (van Weeren *et al.*, 1990). This could make the use of skin markers less reliable in horses, suggesting the need for bone markers for HJC calculation in the first instance. Subject-specific data obtained from medical imaging have improved HJC accuracy in man (Fiorentino *et al.*, 2015) although this approach can increase exposure to ionising radiation and has longer post-processing time and associated costs (Kainz *et al.*, 2015). Magnetic resonance imaging or computed tomography of the horse hip joint in vivo is limited due to the bore diameter of closed MRI and CT systems. Therefore, the aim of this preliminary study is to identify the equine HJC using bone pins in cadavers using a sphere-fitting method.

Methods

Three fresh equine cadavers were used in the study (3-year old 495 kg Standardbred Trotter gelding, 23-year old 583 kg Holsteiner gelding, 7-year old 382 kg Appaloosa gelding). These horses were euthanized based on clinical findings unrelated to the study, and on admission to the clinic owners had given permission for the use of the bodies. Cadaver preparation took place immediately after euthanasia and data collection was completed prior to *rigor mortis* onset. Two horses were placed in right lateral recumbency and one in left lateral recumbency (dependent on their position at euthanasia). Drill bits (5mm diameter) were drilled into the upper most pelvic limb at the Tuber Coxae (TC), Tuber Sacrale (TS), Tuber Ischium (TI), cranial part of the Greater Trochanter (GT), Third Trochanter (TT), and the lateral Femoral Condyle (FC). Reflective markers (15mm diameter) were attached to each of the bone pins (Figure 1). The pelvis was not fixed for logistical reasons.

Figure 1 – (a) Locations of the Tuber Coxae (TC), Tuber Ischium (TI), cranial part of the Greater Trochanter (GT), Third Trochanter (TT), and lateral Femoral Condyle (FC) on horse 1. Note that the Tuber Sacrale (TS) is not visible in this image (b) Isolated pelvis and femur

bone specimen from an unrelated horse, placed in a similar orientation as the horse in image 1a. The x,y,z coordinate system is displayed.

Kinematic data were collected using eight infrared cameras (Eagle Digital Real Time System, Motion Analysis Corp., USA) and kinematic software (Cortex 1.3) sampling at120Hz whilst an experienced equine orthopaedic surgeon manually moved the limb through three cycles of pro-and retraction, ab-and adduction and circumduction (cranial-lateral-caudal-medial-cranial) of the uppermost pelvic limb. Accuracy of the functional method does not rely on repeated motion patterns being highly comparable, although similar movement patterns were produced from visual inspection of the video and kinematic data.

Kinematic data were processed and smoothed using a 6Hz low pass Butterworth filter. A local coordinate system was defined in the pelvis using the pelvic markers. The x-axis was defined by the TC and TI, the y-axis by the TC and TS, and the cross-product calculated to obtain the normalised z-axis. Therefore the calculated z-axis was orthogonal to the determined x-y plane. Then the cross product of the defined x-axis and calculated z-axis was calculated to obtain the normalised y-axis. As such, the calculated y-axis was orthogonal to the x-z plane. Therefore the local coordinate system was composed of defined x-axis and calculated y- and z-axes. The femoral markers were defined in the local pelvic coordinate system. A least squares method adapted from Jennings (2013) was used to calculate the coordinates of the HJC in the pelvic coordinate system for each of the femoral markers individually, and then the mean HJC location was calculated. The HJC was presented as a percentage of the TC-TI vector magnitude in each of the three axes from the TC.

Results

All movement trials could be used. There was no noticeable trend for increased or decreased movement over the three measurements, indicating that the soft tissues had not loosened or that rigor mortis had occurred during the measurements. Range of craniocaudal displacement (along the x-axis) of FC in the pelvic coordinate system was 105.7 - 316.0 mm across all horses, movement directions and trials. For lateromedial displacement (z-axis), these values were 152.7 - 275.8 mm respectively (Figure 2).

Figure 2 – (a) Craniocaudal range of motion (mm) of the lateral femoral condyle marker in the pelvic coordinate system of each horse and movement trial (b) Lateromedial range of motion (mm) of the lateral femoral condyle marker in the pelvic coordinate system of each horse and movement trial.

Vector magnitude of TC-TI ranged from 515.6-597.9 mm across all horses. The mean (± standard deviation) HJC was located 52.4 % (± 3.9) caudally, 0.2% (±6.5) dorsally, and 19.8% (± 4.2) medially from the TC, based on TC-TI vector magnitude (Figure 3).

Figure 3 – Location of the Hip Joint Centre for each of the femoral markers individually and the average location, presented as a distance from the tuber coxae in the (a) craniocaudal direction (b) dorsoventral direction and (c) mediolateral direction. Values are reported as a percentage (%) of the tuber coxae to tuber ischium vector magnitude. Error bars indicate the standard deviations.

Discussion

This preliminary study reports on the equine HJC, determined using a functional method and bone-fixated markers *in vitro*. The gold standard for HJC quantification in humans is by medical imaging (Kainz *et al.*, 2015). Unfortunately, similar data are not available in the horse therefore the results from the present study cannot be directly compared. However, as the functional method has successfully been used to determine the HJC in man *in vitro* (Cereatti *et al.*, 2009), it is anticipated that the similar approach used in the present study has provided a good initial estimation of the equine HJC.

In the present study, a variety of body types were used (Warmblood, Standardbred Trotter, and Appaloosa) to illustrate the universal application of the proposed HJC. In future studies, ponies and cold blood horses should also be used to quantify the HJC in a more generalised population. Furthermore, data from greater sample sizes of specimens from different breeds or types could provide breed-specific HJC locations for even greater accuracy. This is particularly relevant in light of conformation differences amongst different breeds of horses, e.g. the slope of the pelvis can vary significantly amongst groups/types of elite performance horses (Holmström *et al.*, 1990).

The disadvantage of using fresh specimens with all soft tissue remaining in situ is that soft tissue changes occur with time after death. However, changes in range of craniocaudal and lateromedial displacement of the distal femur between first and last passive movements performed in the present study were minimal and did not display an increasing or decreasing pattern, therefore it is unlikely that tissue changes influenced the study findings. Drilling through the muscle was chosen over dissection of the limb down to only the joint capsule and its ligaments to retain a more natural range of motion, as step-wise reduction of soft tissues has been shown to reduce joint stiffness (Valentin *et al.*, 2012).

In the present study we used individual markers drilled into bony landmarks of the pelvis and proximal and distal femur. Although previous work has reported that skin-fixated distal marker clusters as less prone to soft tissue artefacts (Cereatti *et al.*, 2009) and therefore probably more reliable, the most proximal femoral marker (GT) in the present study had the smallest standard deviation for two of the three planes. This illustrates the advantage of using bone pins rather than skin fixated markers. Although marker clusters are recommended over individual markers placed over bony landmarks when non-sagittal plane movements are performed (Besier *et al.*, 2003; Borhani *et al.*, 2013), sagittal plane movement is the primary movement available in the equine hip, therefore the use of individual markers should not have greatly influenced the study results.

In humans, the femoral head is described as choncoid rather than strictly spherical (Menschik, 1997) which may affect movement of the femoral head in the acetabulum and thereby influence the HJC. However, translations of the HJC were of the same magnitude in cadavers using bone pins as that of a mechanical analogue modelled using a spherical hinge (Cereatti *et al.*, 2010). Although the femoral head of the horse is commonly described as semi-spherical (Budras *et al.*, 2001), it shows less convexity in its cranial half than in its caudal half (Figure 4). As the horse has a relatively large fovea, a strong ligamentum capitis femoris, an accessory ligament and the labrum supplementing the socket shape of the acetabulum, only a small degree of translation is anticipated in this joint. Nonetheless it is recommended that a study similar to Cereatti and colleagues (2010) is performed in the horse to determine the influence of femoral head shape and translation on HJC location.

Figure 4 – Non-spherical head of the femur (less convexity in the cranial half than the caudal half)

A potential source of error in HJC estimation when using the functional method is displacement of the pelvis when the femur is moved. The pelvis was not fixed to the supporting surface in the present study for logistical reasons, although not deemed necessary either, as the mass of the cadaver was judged to be sufficient to minimise gross pelvic displacement. Furthermore, it is suggested that a least squares approach such as that used in the present study can minimise the error source caused by a mobile pelvis (Piazza *et al.*, 2004). An alternative approach would be to use a Monte Carlo simulation as described by De Momi *et al* (2009), which uses an initial estimation of the HJC described by Siston and Delp (2006). This has shown good reliability and accuracy regardless of large pelvic displacements, therefore this method might be considered for future experiments investigating the HJC in horses.

Limited range of hip joint motion can be a possible error source in HJC estimation when using the functional method (Piazza *et al.*, 2001; Piazza *et al.*, 2004). Although the range of flexion-extension in the equine hip joint is large, movement in other directions is limited (Dyce *et al.*, 2010). The International Society of Biomechanics (ISB) recommends the functional method for the identification of the HJC in people with adequate hip range of motion, and the predictive method in populations with limited hip range of motion (Wu *et al.*, 2002). As the functional method is more accurate than the predictive method (Fiorentino *et al.*, 2015, Sangeux *et al.*, 2011), the functional method was used in the present study however future work should also quantify the equine HJC using the predictive method. This will determine which method of HJC estimation is most robust in the horse.

Although further work is required to establish the reliability of the findings reported in the present study, this preliminary work is an important and necessary step for the development of musculoskeletal models of the equine pelvis. In the last decade, musculoskeletal modeling of the equine forelimb has made considerable advancements (Harrison *et al.*, 2012, Swanstrom *et al.*, 2005, Zarucco *et al.*, 2006). This is in contrast to the equine hindlimb, likely due to the complex function of the pelvic girdle. It is anticipated that the results presented here can assist in the development of musculoskeletal models of the equine pelvic limb.

In conclusion, the present study provides a preliminary estimation of the HJC in the horse using a functional method. Future HJC studies in horses should use other methods commonly applied in humans including the predictive method and imaging, such that comparisons can be made to evaluate the reliability of the results reported.

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Conflict of Interest

None of the authors have a conflict of interest to declare.

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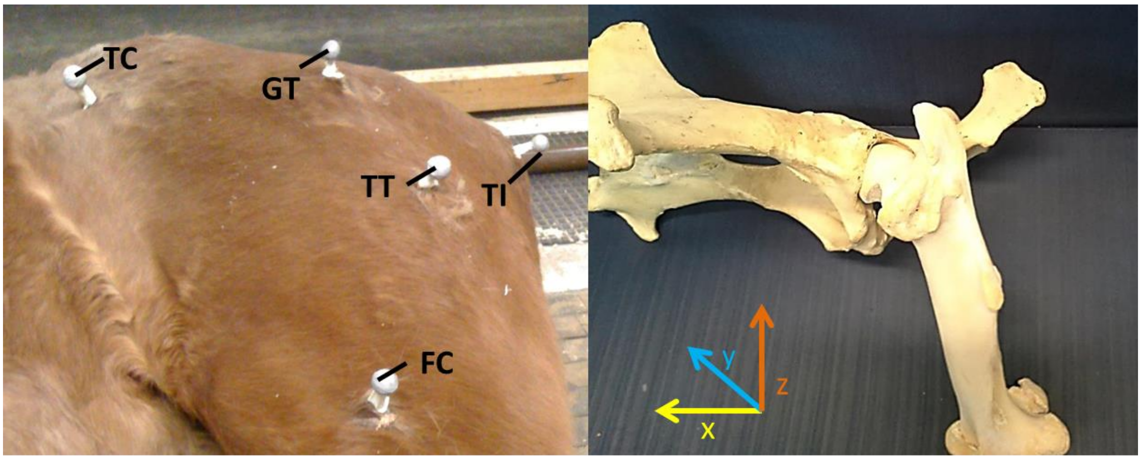
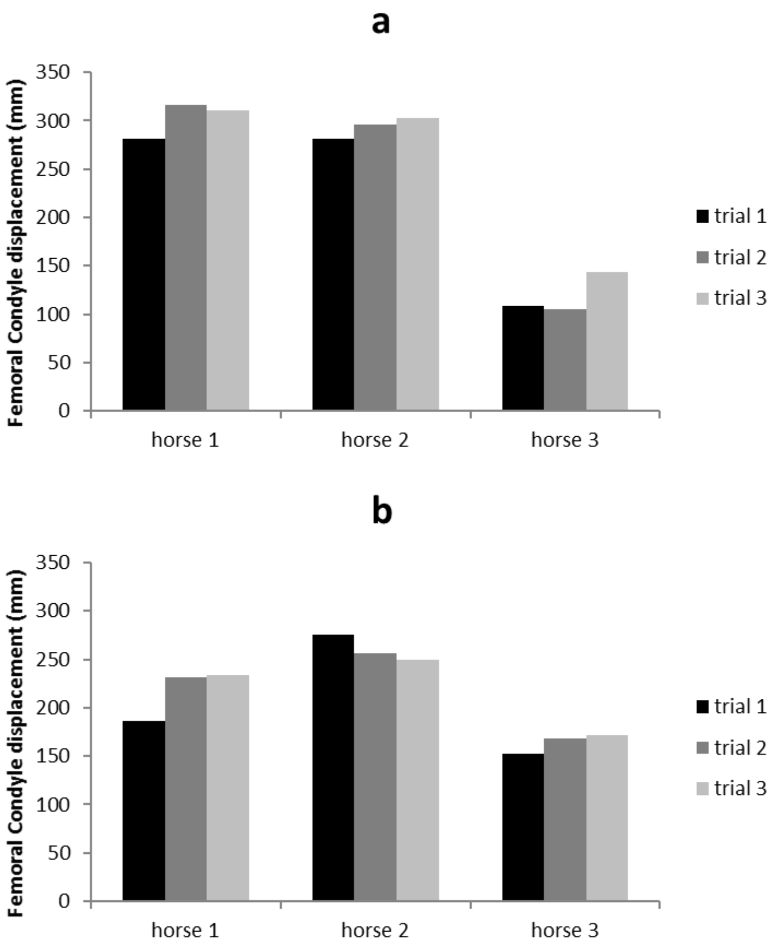
Fig1



TC
GT
TT
TI
FC
y
z
x

Fig2



a
Femoral Condyle displacement (mm)
350
300
250
200
150
100
50
0
horse 1
horse 2
horse 3
trial 1
trial 2
trial 3
b
Femoral Condyle displacement (mm)
350
300
250
200
150
100
50
0
horse 1
horse 2
horse 3
trial 1
trial 2
trial 3

Fig3

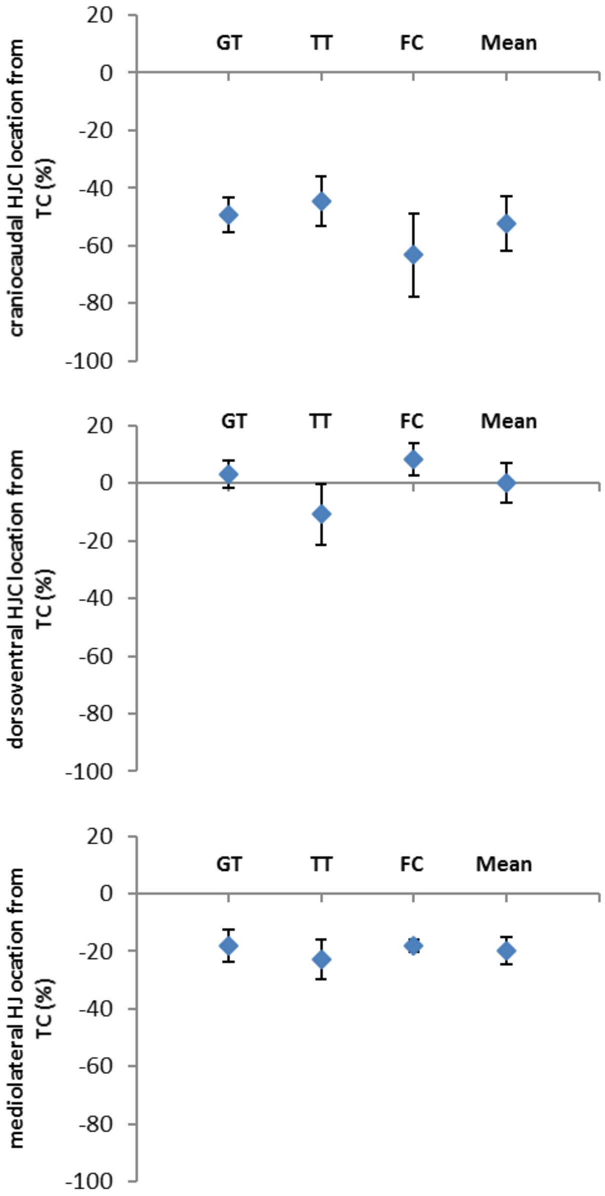

20
0
-20
-40
-60
-80
-100
GT
TT
FC
Mean
craniocaudal HJC location from TC (%)
dorsoventral HJC location from TC (%)
mediolateral HJ ocation from TC (%)

Fig4