Journal of Biomechanics 47 (2014) 1220–1224

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Accuracy and precision of gait events derived from motion capture in horses during walk and trot

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ARTICLE INFO

Article history:
Accepted 16 December 2013

Keywords:
Gait analysis
Equine
Locomotion
Method comparison
Stance
Hoof-on
Gait event
Algorithm

ABSTRACT

This study aimed to create an evidence base for detection of stance-phase timings from motion capture in horses. The objective was to compare the accuracy (bias) and precision (SD) for five published algorithms for the detection of hoof-on and hoof-off using force plates as the reference standard.

Six horses were walked and trotted over eight force plates surrounded by a synchronised 12-camera infrared motion capture system. The five algorithms (A–E) were based on: (A) horizontal velocity of the hoof; (B) Fetlock angle and horizontal hoof velocity; (C) horizontal displacement of the hoof relative to the centre of mass; (D) horizontal velocity of the hoof relative to the Centre of Mass and; (E) vertical acceleration of the hoof. A total of 240 stance phases in walk and 240 stance phases in trot were included in the assessment. Method D provided the most accurate and precise results in walk for stance phase duration with a bias of 4.1% for front limbs and 4.8% for hind limbs. For trot we derived a combination of method A for hoof-on and method E for hoof-off resulting in a bias of −6.2% of stance in the front limbs and method B for the hind limbs with a bias of 3.8% of stance phase duration.

We conclude that motion capture yields accurate and precise detection of gait events for horses walking and trotting over ground and the results emphasise a need for different algorithms for front limbs versus hind limbs in trot.

1. Introduction

Objective assessment of gait is an efficacious clinical tool in human medicine (Wren et al., 2011) and is rapidly evolving in veterinary medicine as a supplement to subjective assessment of lameness (Gillette and Angle, 2008; Keegan, 2007). Current techniques for lameness evaluation use inertial sensors placed on head, trunk and sacrum. Kinematics of the distal limb could be of further potential (Moorman et al., 2012; Olsen et al., 2013). Motion capture and force plates have the potential to aid assessment of deficits in neuro-motor control on a spinal or supraspinal level because spatial and temporal characteristics are primarily controlled through the spinal and supra-spinal neural pathways (Martinez et al., 2012; Rossignol and Frigon, 2011). Classification of movement as normal, or abnormal, can be based on a combination of subjective clinical examination and objective analysis of gait (Keegan et al., 2012; Lord et al., 2013; Wren et al., 2011).

Interpretation of data from gait and locomotion requires reproducible and evidence based techniques for data processing. Reproducible and uniform segmentation into spatial and temporal characteristics (Lord et al., 2013) with force plates is considered the reference standard to detect timing of hoof-contact (Olsen et al., 2012; Sutherland, 2002; Witte et al., 2004).

The use of force plate arrays to segment data into strides often restricts locomotion to a straight line and limits the number of strides. Motion capture derived kinematics can be adapted for outdoors use (Hobbs et al., 2011) and potentially also used on a circle for detailed horse locomotion.

The force plate arrays are rarely portable, and thus, there is a need for accurate and precise evidence-based and shared algorithms for the detection of gait-events and kinematic characteristics based on motion capture signals alone.

Different approaches have been investigated estimating timings for foot-on/off from motion capture for humans on a treadmill and walking over ground (Zeni et al., 2008) and humans running (Leitch et al., 2011), cats walking over ground (Pantall et al., 2012) and horses during walk (Peham et al., 1999) and trot (Galisteo et al., 2010). However, none of these algorithms have been tested and compared for horses during walk and trot on front and hind limbs.

The aim of this study was to provide evidence for gait event detection algorithms based on motion capture. The objective was to compare accuracy (bias) and precision (standard deviation of

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http://dx.doi.org/10.1016/j.jbiomech.2013.12.018

bias) for three algorithms developed for use in humans (Leitch et al., 2011; Zeni et al., 2008) and two developed for use in horses (Galisteo et al., 2010; Peham et al., 1999) using force plates as the reference standard.

2. Materials and methods

2.1. Animals

Six mares of mixed breeds (height: 1.45 ± 0.11 m; body mass: 450 ± 70 kg) from the teaching herd at the Royal Veterinary College (RVC) were included in the study. The procedures were approved by the ethics and welfare committee at the RVC and complied with the European Animal (Scientific Procedures) Act of 1986.

2.2. Data acquisition

The horses were walked (1.15 ± 0.07 m/s) and trotted (2.59 ± 0.17 m/s) across a 25 m runway with a 4.8 m data collection area with eight seamlessly embedded force plates (type 9287BA, Kistler Instrumente AG, Switzerland) sampling at 1000 Hz and a synchronised 12-camera infrared motion capture system (Oqus 3 and 5 series, Qualisys AB, Gothenburg, Sweden) sampling at 240 Hz.

Reflective half sphere markers with a diameter of 26 mm were placed on the horses at the right and left side over the estimated centre of mass (CoM) as described by Buchner et al. (2000), on each leg over the lateral hoof wall, at the proximal and distal dorsal hoof wall, laterally over the fetlock joint and laterally over the head of the fourth metacarpal/metatarsal bone (Fig. 1).

Fig. 1. Illustration of the marker placing on a horse from the trials. The markers on the Proximal metacarpus/metatarsus, on the fetlock joint and at hoof coronet are used in algorithm B for the detection of fetlock joint angle. The marker on the lateral hoof is used in method C and D. The distal dorsal hoof marker is used in method A, B and E to detect horizontal hoof speed and vertical acceleration.

3. Data processing

The motion capture files were pre-processed using dedicated commercial software (Qualisys Track Manager, Qualisys), converted into tab delimited text files (.tsv) with separate columns for x y and z coordinates and processed in MATLAB (R2011a, The MathWorks Inc., Natick, MA, USA). Hoof-on and hoof-off were extracted from the force plates using a semi-automated custom written MATLAB script and a threshold of 50 N for beginning and end of stance phase. Strides are defined as the time from a single hoof contacts the ground until that same hoof contacts the ground again and strides were discarded if they were outside or between force plates.

Hoof-on and hoof-off were extracted from motion capture using the following algorithms A–E (for further details, see supplementary table S1): Algorithm A (Peham et al., 1999) detects the beginning and ending of stance based on horizontal velocity of the distal dorsal hoof. The algorithm defines stance as the mode of fore-aft hoof velocity during each stride cycle. Galisteo et al. (2010) suggested algorithm B for use with video-based kinematics during over ground trot. Algorithm B is a modification of algorithm A (Peham et al., 1999) where hoof-on is detected using the absolute minimal fore-aft hoof velocity as a threshold. Hoof-off is defined as the angle of fetlock extension greater than 180°. However, several horses in this study never reached that angle, and the number of detected strides markedly improved by changing the threshold angle to 190°. Algorithm C and D (Zeni et al., 2008) were based on two slightly different analyses of maximal protraction and retraction of the limbs. In algorithm C the minimum and maximum peaks in horizontal displacement of the hoof relative to the marker at the CoM defined hoof-on/off. In algorithm D, the horizontal hoof velocity relative to the horizontal velocity of the marker at the CoM defined hoof-on/off as the frame where the relative velocity changed between positive and negative (zero crossing of the relative velocity). Algorithm E, modified after Leitch et al. (2011), defined hoof-on/off as the time when vertical acceleration of the hoof changed between positive and negative.

For algorithm B (hoof-on only), A and E, the distal dorsal marker on the hoof was used because it is closer to the pivot point of the hoof during break-over (Witte et al., 2004). Method C and D used the lateral hoof marker.

3.1. Statistics

Statistics were calculated using R (R Core Team, 2013) and the package MethComp (Carstensen et al., 2012) for agreement analysis corrected for replicate measurements per horse as described by Bland and Altman (2007) and Carstensen et al. (2008) with a correction for random effects of animal. Accuracy is defined as the mean difference between motion capture and force plates (bias) and precision as the standard deviation (SD) of the mean difference between motion capture and force plates (accuracy). For interpretation, the best accuracy and precision is the lowest towards minimising measurement error. Stance phases were removed if the duration of stance varied more than two standard deviations from the mean.

4. Results

A total of 240 stance phases in walk and 240 stance phases in trot were included in the analyses with 10 stance phases per limb per horse. A total of 14 outlier stance phases were removed for walk and 20 outlier stance phases were removed for trot. Accuracy and precision for walk and trot are summarised in Table 1. For walk, algorithm D had the best precision in all gait events except for hind limb hoof-on. Algorithm D is the second most accurate

Table 1
Agreement and descriptive statistics for hoof-on, hoof-off and stance for 240 strides pooled from six horses during walk and trot. Results are for each of the five kinematics-based methods A to E compared to force plates as the reference standard. All values are in ms.

			Front limb		Hind limb	
Gait	Gait-event	Algorithm	Acc[a]	Prec[b]	Acc[a]	Prec[b]
Walk	Hoof-on	(A)	−5.2	18.8	−19.8	15.0
		(B)	25.6	23.0	14.1	28.4
		(C)	31.9	11.4	12.7	10.4
		(D)	31.9	11.4	12.6	10.5
		(E)	43.8	20.6	29.2	19.5
	Hoof-off	(A)	−5.7	20.3	−13.6	32.9
		(B)	−35.0	12.8	−26.2	29.1
		(C)	−0.4	5.9	−23.7	20.5
		(D)	−0.2	5.8	−23.7	20.5
		(E)	−3.0	8.3	−21.3	27.2
	Stance	(A)	−0.4	26.9	6.0	36.2
		(B)	−60.4	26.4	−40.4	41.5
		(C)	−32.2	12.6	−36.4	21.9
		(D)	−32.0	12.5	−36.3	21.9
		(E)	−47.0	22.6	−52.4	27.7
Trot	Hoof-on	(A)	17.0	16.6	25.4	23.5
		(B)	−6.9	28.2	6.3	21.3
		(C)	−48.8	11.9	−26.2	11.9
		(D)	−48.1	10.5	−26.2	9.3
		(E)	−57.5	16.5	–	–
		(A+E)	16.2	14.2	–	–
	Hoof-off	(A)	−3.8	25.5	−12.3	42.5
		(B)	33.7	30.2	21.5	21.9
		(C)	20.0	9.0	38.8	20.6
		(D)	20.1	9.0	38.8	20.6
		(E)	2.3	9.9	–	–
		(A+E)	1.8	22.5	–	–
	Stance	(A)	−20.5	27.6	−36.7	45.1
		(B)	41.3	42.0	15.3	33.4
		(C)	68.9	11.9	65.2	27.5
		(D)	68.9	11.9	65.2	27.5
		(E)	59.5	20.3	–	–
		(A+E)	18.3	28.7	–	–

Accuracy and Bias are calculated using R (R Core Team, 2013) and the package MethComp (Carstensen et al., 2012) for agreement analysis corrected for replicate measurements per horse as described by Bland and Altman (2007) and Carstensen et al. (2008) with a correction for random effects of animal.
The methods A. – E. are described and referenced in the text. They are based on analysis of (A) horizontal hoof velocity; (B), horizontal hoof velocity and fetlock angle; (C) maximal protraction and retraction defined by the relative displacement of the hoof compared to Centre of Mass; (D), maximal protraction and retraction defined by the relative velocity the hoof compared to Centre of Mass and (E) vertical acceleration of the hoof.

[a] Accuracy (bias): the average of FP − method_{a-E}.
[b] Precision (SD of bias): Standard Deviation (SD) of the accuracy.

method for stance phase duration in front and hind limbs and has a detection rate of 76–78% of the stance phases.

In trot, algorithm C and D are the most inaccurate methods for hoof-on and stance phase duration. For the front limbs algorithm A has the best combination of accuracy and precision for hoof-on during trot and algorithm E is the most accurate and precise method for hoof-off (Table 1). A combination of algorithm A for hoof-on and algorithm E for hoof-off in the front limbs lead to detection of 78% of the stance phases (Table 2). In the hind limbs, algorithm B is the most accurate method for hoof-on and also the most accurate for stance phase duration. Algorithm B detects 78% of the stance phases.

5. Discussion

Peham et al. (1999) found an accuracy of 1.4% for stance phase duration for motion capture compared to force plates (algorithm A). We find a similarly good accuracy of 0.6% for algorithm A for front limb, and −0.5% for hind limb stance phase duration. Algorithm D is more precise than algorithm A (Tables 1 and 2).

Pantall et al. (2012) compared kinematics-derived gait-event detection algorithms to force plates for use in cats during walk based on De Witt (2010) and trot based on Ghoussayni et al. (2004), Hreljac and Stergiou (2000), O'Connor et al. (2007) and Zeni et al. (2008). De Witt (2010) found maximal protraction and retraction (our algorithm C and D) to give the best precision in walk in agreement with our findings.

Algorithm A has a better accuracy than algorithm D in walk, but D is more consistent. Algorithm D is also advantageous for use in walk, as it is based on lateral hoof markers. The distal dorsal hoof markers easily fall off as they are dragged along the floor or hind limb markers hit the front limb hoof. Algorithms C and D have poor accuracy in trot compared to A, B and E. Thus, it is notable that the maximal protraction and retraction for C and D do not correspond to hoof-on and hoof-off in trot. Peham et al. (1999) do not discriminate between accuracy and precision for front limbs versus hind limbs. Our results support that it is not necessary to analyse the results separately for front limb and hind limb kinematics in walk, however, it is necessary to use different algorithms for hind limbs and front limbs during trot. Olsen et al. (2012) find algorithms of different accuracy and precision for gait event detection using inertial measurement units on the distal limb during walk.

For trot, algorithm A has a better combination of accuracy and precision to detect hoof-on, whereas algorithm E has the best accuracy and precision to detect hoof-off for the front limbs. We therefore created a revised algorithm both applying algorithm A and E in trot for the front limbs. We found this combination to have the best accuracy and precision for hoof-on and stance phase duration, whereas algorithm E alone is better at detecting hoof-off in the front limbs.

We recommend the use of the combined algorithms A and E to be used in the front limbs unless accuracy and precision for hoof-off is more important. In this case, algorithm E is recommended. For the hind limbs, algorithm B has the best (lowest) accuracy and precision to detect hoof-on and algorithm A to obtain stance duration.

A study by Witte et al. (2004) utilises hoof-mounted accelerometers to obtain timings for front limb hoof-on and hoof-off in walk and trot compared to force plates. The average force plate derived stance phase duration for walk was 753.4 ms. Our motion capture-derived algorithms are more accurate to detect hoof-off in the front limbs with −0.2 ms (measurement error; ME: 0.03%) compared to the hoof-mounted accelerometers with a mean error of 3.6 ms (ME: 0.48%). Our motion capture-derived algorithms are slightly less accurate for hoof-on with a bias of −5.2 ms (ME: 0.69%) compared to 3.6 ms (ME: 0.48%) for the hoof-mounted accelerometers. The average force plate derived stance phase duration for trot was 300.5 ms. Our motion capture-derived algorithms are comparably accurate for hoof-off with 2.3 ms (ME: 0.77%) relative to the hoof-mounted accelerometers with a mean error of 2.4 ms (ME: 0.80%). Our motion capture-derived algorithms were markedly less accurate for hoof-on with a bias of 6.9 ms (ME: 2.3%) compared to hoof-mounted accelerometers that had a mean error of 1.8 ms (ME: 0.80%). All measurement errors are below 7% and can therefore be considered acceptable. However, accelerometers have a better accuracy for front limb hoof-on. The previous reports do not include precision of the accelerometers neither accuracy nor precision for hind limb hoof-on and hoof-off.

Combining algorithms makes it possible to obtain timings for hoof-on/off and duration of stance phase in walk and trot with using motion capture with a measurement error less than −0.6%

Table 2
Characteristics and measurement error for duration of stance in walk trot for front and hind limbs.

		Front limb				Hind limb			
Gait	**Algorithm**	**Stride %[a]**	**Stance duration[b] (ms)**	**SD[c] (ms)**	**% Error[d]**	**Stride %[a]**	**Stance duration[b] (ms)**	**SD[c] (ms)**	**% Error[d]**
Walk	(A)	93	757.8	59.6	−0.6	94	755.7	58.7	−0.5
	(B)	73	818.7	59.3	8.7	73	798.4	65.4	5.1
	(C)	92	787.1	53.5	4.5	91	798.3	53.7	5.1
	(D)	76	787.5	52.9	4.5	78	801.7	52.6	5.6
	(E)	59	796.4	60.0	5.7	67	819.1	59.0	7.8
	Force plates	100	753.4	54.5	–	100	759.5	52.8	–
Trot	(A)	98	279.6	41.4	−7.0	87	255.8	28.2	−12.1
	(B)	78	342.2	53.1	13.9	78	302.7	23.5	4.1
	(C)	91	371.2	31.2	23.5	93	356.3	21.3	22.5
	(D)	59	369.5	32.1	23.0	66	356.0	29.6	22.4
	(E)	70	356.4	39.0	18.6	–	–	–	–
	(A+E)	78	320.2	41.1	6.5	–	–	–	–
	Force plates	100	300.5	31.6	–	100%	290.9	27.7	–

[a] Stride%: The percentage of force plate strides detected by each method. Only strides detected by the force plates were included (force plate stride detection = 100%).
[b] Stance duration: average stance duration by each method.
[c] SD: standard deviation of stance duration.
[d] % Error: The difference between the stance phase duration measured by each method compared to the stance phase duration measured with the force plates in percentage of the force plate duration.

for walk and 6.5% for trot. An evidence-based algorithm shared in the public domain with good accuracy and precision has implications for improved understanding of motor control, neurologic deficits, lameness and analysis of outdoor kinematics.

6. Study limitations

One important limitation of the present study and in fact most studies of gait event detection algorithms is the lack of documentation of the effect of different surfaces. We used a hard surface where the kinetic and kinematic behaviour of beginning and end of stance is different, when walking or trotting over grass, sand, or other softer surfaces (Chateau et al., 2009; Martino et al., 2013). Another limitation is the applicability to canter and gallop, as we have only investigated walk and trot.

Conflict of interest

We have no conflicts of interest to disclose.

Acknowledgements

We are grateful to Christian Peham for sharing his gait event detection script and to the funding bodies at University of Copenhagen; "Jubilæumsfonden", the Research School KLINIK, Department of Large Animal Sciences and the Danish Agency for Science Technology and Innovation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2013.12.018.

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