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Stance phase detection by inertial measurement unit placed on the metacarpus of horses trotting on underwater treadmill at different water heights

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1. Introduction

High-intensity training causes micro-to-large lesions on the horse's musculoskeletal system, leading to long rest periods, muscle loss and reduced physical condition (King 2016).

In horse training, the underwater treadmill (UWT) is often used because it significantly reduces the ground impact on the bones and muscles (King 2016). So it may help to maintain physical condition during a period of treatment. Consequently, monitoring horse locomotion can be considered as a priority to evaluate the work load in the UWT (Arnold et al. 2019).

The detection of gait events as spatio-temporal parameters on a treadmill (Sapone et al. 2020) and in the field (Hatrisse et al. 2022) has required specific methods using IMUs attached to the hoof to retrieve accurate information on stride events. However, fixing the IMUs to the hoof is complex and challenging. Fastening the IMUs on the cannon bone is an alternative and has the advantage of being easily integrated into boots (Sapone et al. 2020). The aim of this study was to test and validate an existing method, developed by Hatrisse et al. (2022), for automatic detection of Foot-on and Heel-off event using an IMU mounted on the horse metacarpus (cannon bone), in UWT conditions at different water heights. Hoof-mounted sensors were used to obtain reference data.

2. Methods

2.1. Data acquisition

Six sound horses of standardbred and thoroughbred breeds were included in the study. Horses were equipped with five synchronized IMUs (Blue Trident,

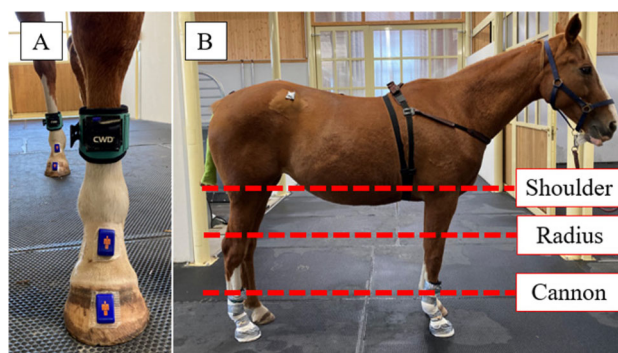


Figure 1. IMUs localization on the horse (A, B) and representation of the different water height (B).

dual-g sensors, Vicon Motion Systems Ltd United Kingdom) with a full-scale range of 16g (Low-g), 2000°/s, 16 bits, sampling at 225Hz. IMUs were positioned on the withers, on the cannon bone of the right forelimb and hindlimb, and the last two IMUs were mounted on the toe of the right front and hind hoof of the horse (Figure 1A and B). Four different conditions were tested, based on water heights: off-water and three water heights corresponding to the cannon bone, radius and shoulder level (Figure 1B). Horses trotted at 3.5 m/s and data were collected during successive twenty seconds for each condition.

2.2. Data processing

Following data acquisition, the first step was to get the Foot-on and Heel-off events from the hoof-mounted IMUs, based on the methods developed by Tijssen et al. (2020) and already used by Hatrisse et al. (2022).

Then, the second step of the data processing focused on the Foot-on and Heel-off detection from the data of the cannon bone mounted IMUs, in the different water height conditions. As in 'on-field' conditions (Hatrisse et al. 2022), in underwater conditions, the cannon bone X-axis acceleration signal (cranio-caudal axis) showed the same repeatable peaks corresponding to Foot-on and Heel-off events. The algorithm, described by Hatrisse et al. (2022), was applied on these data.

Due to underwater conditions, the swing phases were modified. The algorithm had to be adapted for strides windowing method. All strides were windowed between each maximum peak of the cannon bone Y-axis gyroscope (transversal axis), using the method described by Sapone et al. (2020), corresponding to the swing phase of each stride and allowing centering the stance phase in the processing window. To ensure an accurate strides windowing in all water height conditions, a 4 order Butterworth low-pass filter with 0.025Hz cut-off frequency was applied to get first the main peak on the cannon-bone Y-axis gyroscope

Table 1. Bland–Altman comparison of both methods (in % of stride duration).

Water Height	Event	Right Forelimb				Right Hindlimb			
		Bias	SD	ULA	LLA	Bias	SD	ULA	LLA
No water	Foot-on	0.32%	3.34%	6.86%	−6.22%	−0.08%	1.37%	2.61%	−2.77%
	Heel-off	0.28%	1.60%	3.42%	−2.86%	−0.33%	4.63%	8.74%	−9.40%
Cannon	Foot-on	1.06%	2.06%	5.09%	−2.97%	−0.42%	2.16%	3.81%	−4.64%
	Heel-off	0.86%	1.10%	3.02%	−1.30%	0.01%	2.73%	5.37%	−5.35%
Radius	Foot-on	0.65%	2.10%	4.76%	−3.46%	−0.03%	1.57%	3.04%	−3.10%
	Heel-off	0.51%	0.91%	2.30%	−1.27%	0.06%	1.68%	3.35%	−3.24%
Shoulder	Foot-on	1.06%	3.67%	8.26%	−6.14%	−0.94%	4.02%	6.93%	−8.82%
	Heel-off	0.32%	5.18%	10.47%	−9.82%	0.44%	2.89%	6.10%	−5.23%

Bias, precision (SD), and upper/lower limits of agreement (ULA and LLA) are indicated for each condition.

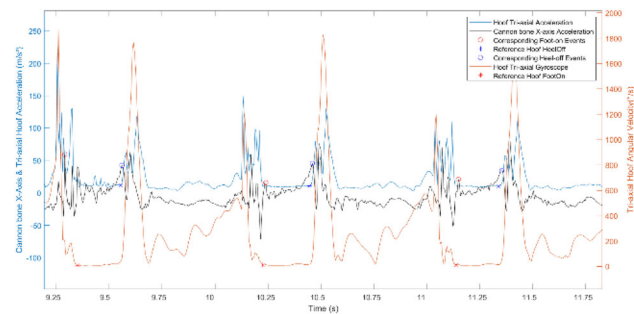


Figure 2. Representation of the hoof Tri-axial acceleration (in m/s^2) and angular velocity (in $^\circ/\text{s}$), and the cannon bone X-Axis acceleration (in m/s^2) of a horse trotting on UWT with a radius water height.

filtered signal. The final maximum peaks were then obtained on the raw cannon bone Y-axis gyroscope, using the time events corresponding to the main peaks on the filtered signal, by windowing the raw signal in the window of forty frames around these peaks. The initial method was retained for the rest of the events detection, only peak height thresholds have been reduced. These minor adaptations are also due to the swing phases modifications in underwater conditions.

Figure 2 shows the reference Foot-on and Heel-off (Tijssen et al. 2020) and highlights the corresponding peaks on the cannon bone X-axis acceleration signal.

2.3. Statistical analysis

All the Foot-on and Heel-off events, detected from the cannon bone IMU, were compared with the reference events, detected from the hoof IMU. The precision and accuracy of Foot-on and Heel-off detection were studied with the Bland–Altman's method (Bland and Altman 2007).

3. Results and discussion

For the Foot-on and Heel-off detection, the precision and accuracy of the developed method are shown in Table 1.

Maximum bias was 1.06%, demonstrating that the tested and adapted method is applicable to different water height conditions. We can deduce that the water height does not highly-influence the bias. We notice that the shoulder water height is a little less accurate as this condition show the highest SD, ULA and LLA. This could be explained by the fact that the higher the water, the greater the horse's efforts (Arnold et al. 2019), the strides become then less reproducible between themselves. This study presents some limitations, notably about the reference events. The reference events were detected visually on the hoof Tri-axial acceleration and Tri-axial angular velocity signals. Although highly repeatable and validated on the ground, this reference method is difficult, if not impossible, to validate with a force plate that cannot be used underwater

4. Conclusions

To conclude, this study presents an adaptation to an original method, to detect stride events under water for different water height conditions. The algorithm modifications increase robustness of detection and allow for automatic detection of stance duration in a context where traditional motion capture technologies cannot be used.

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