Coordination patterns in arm versus body steering strategies in free slalom on a motorcycle: A single case pilot study

Marilee Nugent[1], Stéphane Espié[2], Flavien Delgehier[3], Samir Bouaziz[4].

[1] Università degli Studi di Firenze
[2] Université Gustave Eiffel
[3] Centre national de la recherche scientifique (CNRS)
[4] Université Paris-Saclay

Keywords: motorcycle trajectory control, electromyography, motorcycle rider control.

Abstract

The unique dynamics of PTW trajectory control seem to blend unconsciously with human postural and steering actions. For example, the motorcycle seems to follow where the head turns. Expert riders may claim to steer solely by "looking" and "leaning" while engineers know that counter steer inputs to the steering column are required for efficient direction control. How riders coordinate their steering actions and the relative efficiency of different steering strategies or combination of mechanical inputs has yet to be fully explored. In this pilot study we used electromyography to record activation patterns in arm and back muscles of one experienced rider performing slalom maneuvers at ~40 km/h. The test motorcycle was instrumented with sensors recording rider mechanical inputs and vehicle dynamical outcomes. In 10/20 trials the rider attempted to induce direction changes solely using counter steering technique, in the remaining 10, using lateral body movements. Mean cycle length of vehicle roll was significantly longer in the body steer strategy, consistent with this method being less effective in quick steering. Systematic changes in muscle patterns with steer strategy confirmed that different coordination patterns underly and can characterize different steering methods. These pattern changes were seen as differences in muscle onset/offset times, in burst duration, order of activation, and relative timing. Different phasing between muscle bursts and motorcycle roll peaks seen in the two steer methods provides insights into the relationship between rider actions and PTW dynamics which may allow parsing out of the specific and relative influences of different rider control inputs. This study is intended to provide a basis for further investigations into rider control of trajectory and lean angle. The findings have implications for rider control studies development of training methods as well as improving understanding of the complex dynamic control interaction between rider and motorcycle.

Introduction

How riders produce steering and lateral control on a motorcycle is an important topic of study for understanding rider-two-wheeler interaction. Low/ medium speed maneuvering on a motorcycle, as in the performance of emergency collision avoidance maneuvers, requires efficient steering and balance control inputs from powered two-wheeler (PTW) riders, especially in traffic and urban areas. This is an important skillset having implications for both safety and the criteria and assessment procedures in practical license tests. R&D of smart rider assistive systems can benefit greatly from improved models of rider-PTW control interaction as current rider models are insufficient (Loiseau et al. 2020) to explain how the human central nervous system coordinates curve following and trajectory control actions. In this pilot study we investigated the feasibility of using muscle coordination patterns to provide insights into how riders may vary their steering strategies to control heading and lean changes on a motorcycle. It is unknown to what degree steering technique varies between and even within riders. Individuals may express a preference for using 'counter steering' technique, or may claim to control heading and curve following solely by leaning and looking into the curve. Vehicle kinematic measurements alone cannot provide insights about how riders actually achieve this control, or if they are doing what they say they are doing.

Motorcycle steering skill and efficiency is important to safety, as when trying to avoid an unexpected collision hazard or material on the road surface that may cause a capsize. The dynamics of powered two-wheeled vehicles

(PTWs) determine that lateral/trajectory control are produced by varying combinations of lean and steer torque provided by the riders. Although PTW engineering continues to improve vehicle handling, what riders actually do, and what steering skills or strategies may be optimal has been little studied and remains unclear. Specific technique is not obvious from visual observation of riders. Anecdotally, riders differ in their assumptions of what they do to regulate steer control, which is likely explained as their having acquired highly automated control skills through implicit learning. The fact that multiple and fluctuating versions of body and steer torque inputs can produce the same kinematic outcomes means that vehicle signals alone cannot distinguish between categories of steering technique or style. Indeed, this speaks to the concept of the ‘motor redundancy’ of the central nervous system in voluntary control of movement: multiple solutions are possible for the same motor outcome. For example, theoretically a rider could initiate curve following or direction change using one or more mechanical inputs - counter steer torque applied to the handlebar, lateral mass displacement (e.g. part of all of the trunk), asymmetrical pressure to foot pegs - in various combinations or sequences. In addition the rider can vary which body segments are in line or out of line with the PTW vertical axis (e.g. head, head and shoulders or full hang-off) and size of the angle between body axis and PTW axis. Given that these movement variations result from different joint movement patterns, it should be possible to observe different trajectory control strategies or styles depending on the timing of these control actions and how the rider regulates coupling (i.e. stiffness) across joint segments and between body-PTW interfaces.

In the ongoing project VIROLO++ to study PTW rider curve-taking behaviour, researchers asked riders to use arm versus body inputs to control curve-entering, however data analysis and interpretation has been hampered due to the inability to determine from the vehicle sensor data alone whether the test rider was able to comply with the instructions to voluntarily decouple these inputs (unpublished results) (VIROLO++).

The purpose of this study was to compare PTW angular motion recorded simultaneously with electromyographic (EMG) patterns from the key muscles responsible for PTW lateral (steering and lean angle) control to gain insights into rider-PTW interaction outcomes based on voluntary use of different steer control approaches.

Hypotheses

Hypothesis 1 predicted that the different steering control strategies will require categorically different muscle patterns. These may be seen as differences in phasing between muscles and in the recruitment patterns (roles) for specific muscles, in the body versus counter steer strategy.

Specifically, arm muscles would be expected to show more obvious and regular activation patterns if the rider uses steer torque inputs (ARM) preferentially over body inputs (BODY) to induce direction changes, whereas the reverse would be true for the lateral spine flexors of the trunk and knee extensors.

Hypothesis 2 predicted that given that these 2 different steer strategies would specify changes in the roles of specific muscles, we should also see changes in phasing between muscle burst patterns and vehicle direction changes, for example, low back muscle activity may lead roll changes in BODY steering while arm extension and flexion activity leads back muscle activity in ARM steering.

Methods

Task and protocol

The task chosen to assess muscle and motion patterns in different steer strategies was a free slalom maneuver (alternating right and left steering while traveling forward). In terms of muscle pattern analysis, periodic or rhythmic movements provide a repeatability and regularity of data patterns that is easier to analyze than discrete, random motion patterns. For this pilot study, the second author performed the riding tasks and the first author performed the data collection. Both researchers are experienced motorcyclists in both leisure sport/travel and urban mobility use cases.

For each data recording, the rider performed one of two different steering strategies. In the ARM strategy, he attempted to control direction changes using mainly arm inputs, minimizing body inputs. For the BODY strategy, the rider attempted to control direction changes using mainly body inputs, minimizing inputs from the arms.

All trials performed in first gear. Speed was roughly 40 km/h during the slalom sequences. Two collection sessions were performed in the same day, in the morning and in the afternoon. The EMG sensors were left in place for both sessions, so that individual sensor data would be comparable across all trials. In all, 10 sets of slalom oscillations (5-6 cycles each) were collected for each trial condition. Figure 1 shows performance of the maneuver, instrumentation used and sample kinematic and EMG data. Videos of all trials were recorded on a smart phone. Each data recording included a set of slalom maneuvers for the length of the driveway, moving away from the camera phone (Fig. 1 A), a reversal of direction at the end, and another set of slaloms for the return trip.

Instrumentation and data collection

ELECTROMYOGRAPHY. Muscle activity was recorded using wireless surface EMG (sEMG) sensors (Delsys Trigno™ Mobile system) with 10 mm inter-electrode distance. Sensors contained integrated analog filters providing sEMG signal detection bandwidth from 20-450 Hz and pre-amplification to 909 V_{out}/V_{in}. Each sensor also contains an integrated 9 degree of freedom IMU. Sampling frequencies were 1111.11 Hz for EMG data and 148.15 Hz for IMU accelerometer data.

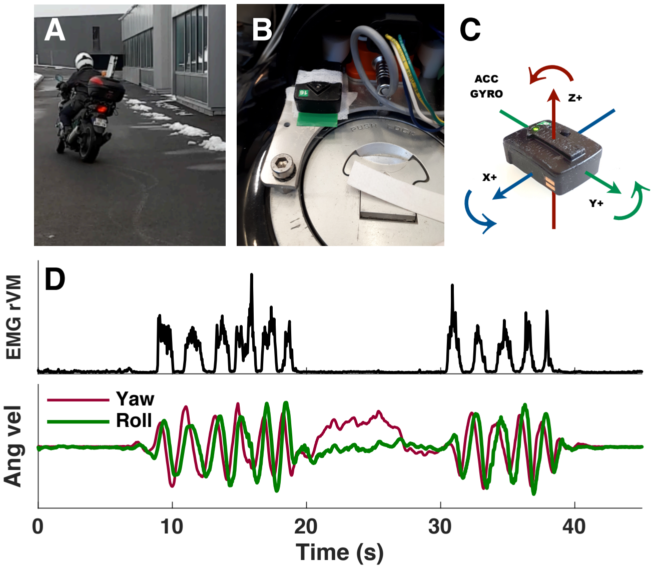
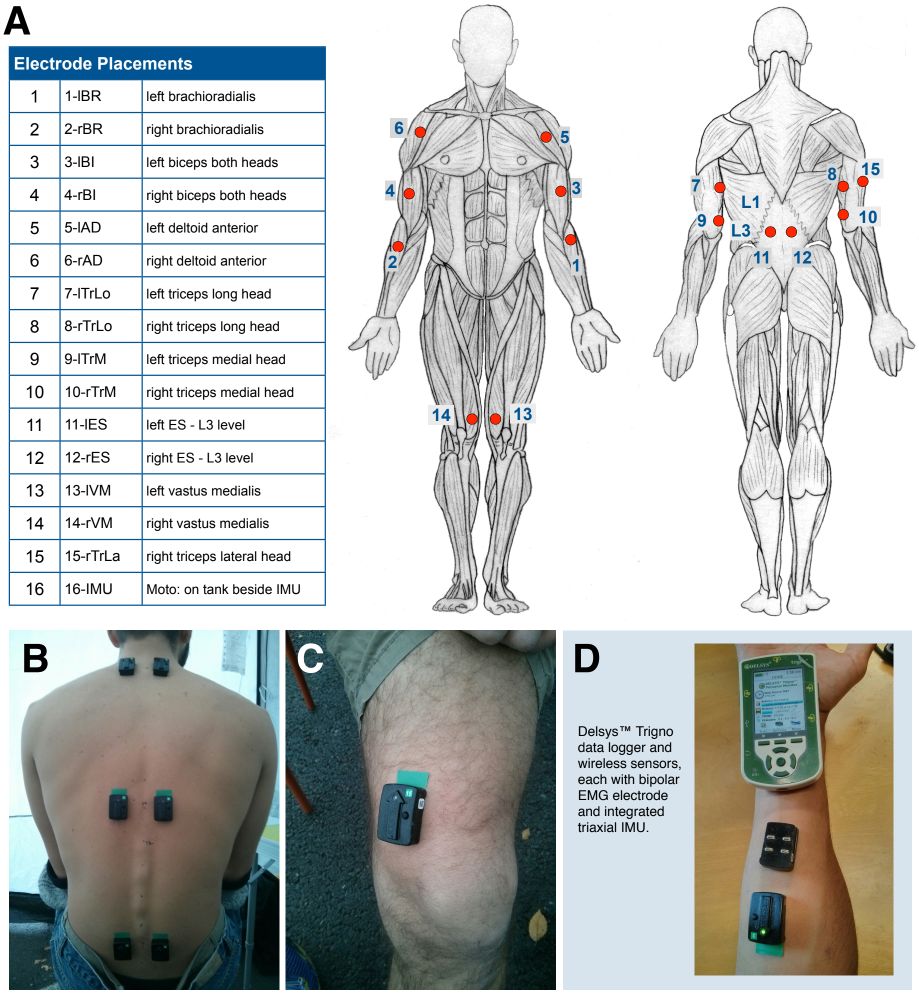


Figure 1 Test vehicle and sample data showing 2 slalom sets. A) Performing the free slalom in a closed parking lot. B) EMG/IMU sensor placed on the motorcycle's tank next to its IMU sensor. C) axes for accelerometer and gyro of the Delsys sensor. D) EMG signal for right vastus medialis (VM - knee extensor) and yaw and roll angular velocities from the sensor placed on the motorcycle's tank.

Since the objective of the study was to differentiate between body versus arm motivated heading changes of the motorcycle, the muscles chosen for recording were those functionally important for pushing and pulling actions of the arms, side bending of the trunk, and pushing or weight support through the leg to the foot pegs An initial data collection session was performed testing a larger number of muscle recording sites in order to determine the ones most representative of steering and leaning actions. The final sites chosen for testing are given in Fig. 2, with the rationale as follows.

Anterior deltoid (AD) provided consistent clear signals associated with arm pushing (shoulder forward flexion)/ direction changes. The erector spinae (ES) muscles of the back straighten or hyperextend the spine when activated bilaterally but perform lateral flexion (side bending) when activated unilaterally. The ES were tested at the 3rd lumbar (L3), 4th lumbar and 12th thoracic levels, since independent activation at different levels has been shown in movements requiring separation of upper and lower spine segments (Nugent and Milner 2017; Nugent et al. 2012). However, L3 alone was deemed sufficient for what (in this rider) appeared to be more global spine motion, being also the recommended site for general back function studies (see SENIAM guidelines (Hermens et al. 2000). The elbow flexors and extensors were expected to be important in alternating handlebar angle in ARM steering. The biceps (BI - elbow and shoulder flexion) and brachioradialis (BR - elbow flexion) were both recorded for pulling actions. Three triceps sites provided somewhat redundant information on elbow extension (pushing), but were all recorded to determine which gave the best signals, due to the difficulty sometimes of obtaining good signals due to skin movement over muscles and the tendency for thicker fat layers in this area. Thicker skin folds are known to reduce sEMG signal amplitude and broaden the burst duration, affecting identified burst onset/offset times (De la Barrera and Milner 1994). These triceps sites were long head (TrLo - bi-articular, acting on both shoulder and elbow), lateral head (TrL), and medial head (TrM - deep to the other two but accessible to sEMG at its distal end). Vastus medialis (VM) was recorded for knee extensor activity (weight bearing on feet, pushing into foot pegs). All muscles were recorded bilaterally except for TrM, as there were only 15 available sensors.



Electrode Placements		
1	1-lBR	left brachioradialis
2	2-rBR	right brachioradialis
3	3-lBI	left biceps both heads
4	4-rBI	right biceps both heads
5	5-lAD	left deltoid anterior
6	6-rAD	right deltoid anterior
7	7-lTrLo	left triceps long head
8	8-rTrLo	right triceps long head
9	9-lTrM	left triceps medial head
10	10-rTrM	right triceps medial head
11	11-lES	left ES - L3 level
12	12-rES	right ES - L3 level
13	13-lVM	left vastus medialis
14	14-rVM	right vastus medialis
15	15-rTrLa	right triceps lateral head
16	16-IMU	Moto: on tank beside IMU

Delsys™ Trigno data logger and wireless sensors, each with bipolar EMG electrode and integrated triaxial IMU.

Fig. 2 sEMG sensors and electrode placements. A) Final electrode configuration/muscle sites used in data collection. B) Examples of different electrode locations for different levels of the erector spinae. C) Sensor placed on vastus lateralis, knee extensor of the left knee. D) Delsys Trigno EMG/IMU wearable wireless sensors, showing one sensor active (affixed), the recording and reference electrodes of the other, and the data logger.

Skin was prepared by shaving, lightly abrading and cleaning with alcohol. Sensors were affixed to the skin with double sided tape. Hypafix® stretchable self-adhesive medical tape was placed over top of each sensor to prevent motion artifacts due to clothing or dislodgement from the skin. The rider wore motorcycle protective clothing to perform the trials.

TEST VEHICLE. The test vehicle was a Honda CBF1000F motorcycle, equipped with sensors to measure vehicle kinematics and the rider's mechanical and control inputs, however, the vehicle data were not analyzed for this paper. Instead, recorded muscle patterns were compared to the motion data recorded for the motorcycle from one EMG/IMU sensor placed on the tank (see Fig. 1 B, C).

Data processing and analysis

EMG/IMU data were recorded on the Delsys data logger which was placed in the rider's jacket pocket. After downloading data trials, EMG data were resampled to 1000 Hz and IMU data were resampled to 100 Hz. All EMG data were demeaned, full-wave rectified and low pass filtered at 8 Hz cutoff using a first order Butterworth digital filter implementing the Matlab© (Mathworks Inc., Natick, MA) 'filtfilt' function. The gyro signals for angular velocity around the y and z axes were used to indicate motion for the motorcycle's roll and yaw motion, respectively, for comparison with the muscle signals. Roll and yaw velocity signals were low-pass filtered using a first order Butterworth digital filter, implementing the Matlab 'filtfilt' function, with a 4 Hz cutoff. Documentation for the wireless EMG system states that the signal group delay (from sensor event to analog output) differs by 48 ms between the EMG and IMU data (Delsys 2019). Thus the EMG time series was corrected by this amount for time synchronization with the IMU data.

All trials were plotted and visually inspected. Start and end times for each set of slaloms were identified from gyro signal plots using cursors. The phasing between roll and yaw for each slalom set was determined by cross-correlating the two filtered, full amplitude-range signals. To calculate mean cycle frequency/period (T) for each set, angular velocity peaks were identified using the Matlab function 'findpeaks'.

Muscle activation patterns were analyzed using two methods, cross-correlation with vehicle motion signals, and determination of burst onsets and offsets. To determine relative muscle timing in the movement cycle, cross-correlations were performed between the filtered vehicle angular velocity signals and filtered muscle signals. Custom Matlab script and the 'xcorr' function with 'coeff' option was used. Since the muscle signal data was rectified (all absolute values), negative values (troughs) of angular velocity signals were first converted to zeros. In this way, each muscle activity pattern was cross-correlated in reference to roll right. Lag results from the cross-correlation function reflect the time of the cross-correlation peak between muscle and angular velocity signal, that is, the time shift required for the best fit between signals. For each slalom set, lag values were normalized as percentages of the mean cycle duration, in order to be more directly comparable and to avoid confounding differences in relative activation timing with differences in movement frequency. Mean lags are given as percentages of median cycle duration (Lag%T). With roll angular velocity as the reference signal 0, positive values indicate muscle burst peak amplitude occurring before right roll velocity peak and negative values indicate muscle burst peak amplitude after right roll velocity peak. Thus, a positive or negative Lag%T value close to zero would indicate strong temporal association between a muscle burst pattern and the direction change. For rhythmic movements, a value of +/- ~50%T would indicate strong association between the muscle and the peak roll velocity in the *opposit*e direction. In other words, right and left alternating muscle activity to produce the slalom pattern.

The resulting Lag%T values provided the relative timing between peak muscle activity and vehicle angular motion, as well as the timing sequence among muscles. It should be noted that these delays also include:

- the muscle electromechanical delay (EMD - the time required for force buildup within the muscle before onset of joint movement (Kamen and Gabriel 2010)
- mechanical delay between onset of joint motion and change in vehicle kinematics
- the delay between displacement
- velocity signals, and any internal sensor delays.

To determine relative onset timing and burst durations (Dur) of key muscles, burst onsets and offsets of selected EMG signals were identified using a standard double-threshold algorithm (Kamen and Gabriel 2010; Micera et al. 2001, Bonato et al. 1998) implemented with custom Matlab script. For each slalom set, these were normalized to mean cycle period T and represented as percentages, to allow direct comparisons between steer strategies. The calculated values of Lag%T, Onset%T and Dur%T statistical analyses of muscle timing.

Statistical analyses

Normality tests for Lag%T, Onset%T and Dur%T were significant, therefore considering also the small sample sizes (i.e. number of slalom sets) statistical analyses were performed using non-parametric tests. Wilcoxon rank sum tests for independent samples were performed to test selected key muscles for effect of steer strategy on:

- lag between yaw and roll velocities
- burst onset time as a percentage of cycle period (T)
- burst duration as a percentage of cycle period (T)

Statistical tests were performed using the Matlab Statistical Toolbox, with significance set at .05.

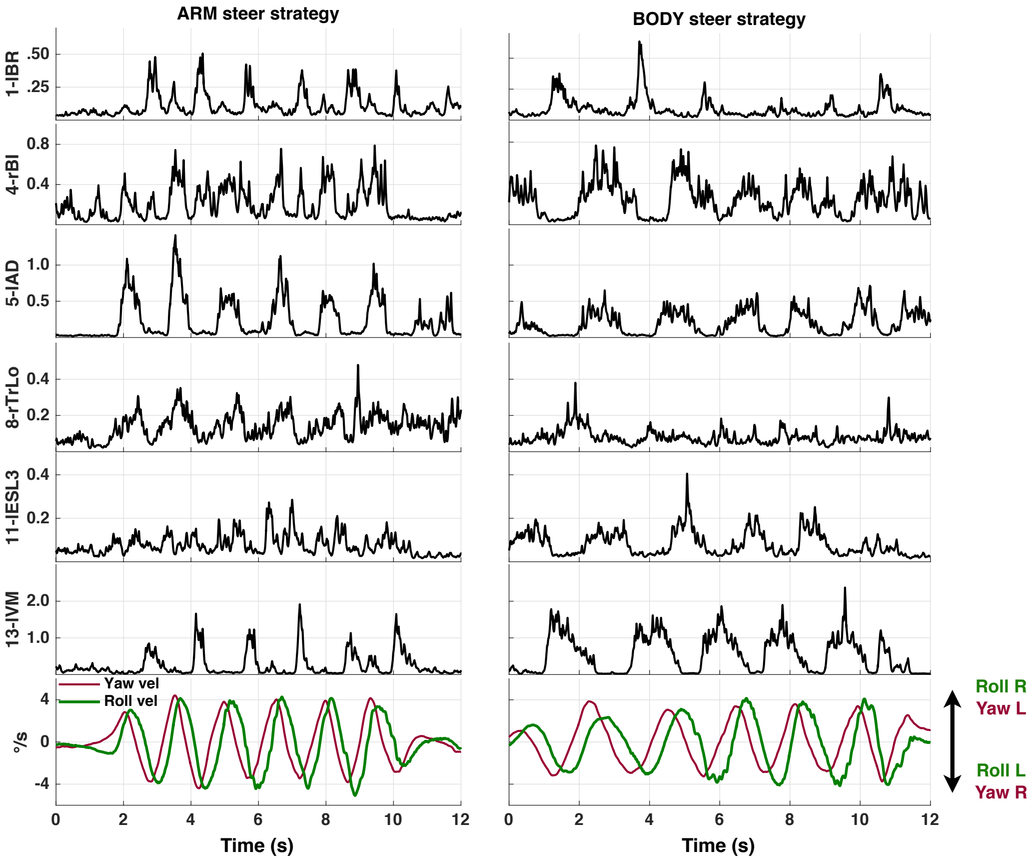


Fig. 3 Examples of slalom set data for the ARM and BODY steering task conditions. Selected muscle EMG in the first 6 rows, vehicle motion in the bottom row. Y-axes scales in each row are the same for direct comparison of signals. Left brachioradialis (lBR), right biceps (rBI), left anterior deltoid (lAD), right triceps long head (rTrLo), left erector spinae, 3rd lumbar vertebral level (lES L3), left vastus medialis (lVM).

Results

All EMG datasets were complete and free from motion artifacts. The final slalom set was excluded from Lag%T analysis since it produced outlier values for most of the muscles, having a roll velocity frequency of 0.90 s compared to the average of 1.23 s. Fig. 3 provides examples of selected muscles plotted with yaw and roll angular velocity, in order to compare the ARM (left column) and BODY (right column) strategies. Axes scales are the same for both columns to allow direct comparison between steer conditions for each muscle. A visual analysis confirms that the AD muscles showed a clear periodic activation to produce the alternating steer actions in the ARM strategy. The BODY also produced clear periodic alternating activity in the AD, but the bursts were lower amplitude and broader. In the ARM trials, elbow flexors (1-lBR, 4-rBI) showed less periodic clarity, and more complex patterns than for the AD, possibly due to having overlaid and/or more variable roles as in the mediation of elbow angle, joint compliance, and transfer of force from shoulder to handlebar grips (point of application of steer torque inputs). As predicted for the BODY trials, the ES muscles had a clear right-left alternating pattern of activity in, whereas in the ARM trials it was difficult to identify activity mirroring the alternating lateral roll of the vehicle. The key muscles associated with the BODY steer strategy were the right & left AD, ES and VM, with periodic activity also evident in the elbow flexors (BR, BI). For the BODY trials, elbow extensor activity was not clearly associated with PTW motion.

Fig. 4 shows roll velocity and EMG plots from an ARM and a BODY trial with examples of onset and offset determinations for 3 representative muscles, lAD, lES, lVM. Median cycle duration was 1.251 s (SD .174 s) in the ARM steer trials and 1.423 s (SD .183) in the BODY steer trials, with median frequency being significantly higher in the ARM steer strategy, p = 0.026, z = -2.23, 0.82 Hz versus 0.72 Hz. This amounts to 14% longer cycle duration in the Body strategy. Median phasing between yaw and roll angular velocities was not different for ARM (20.0% T) and BODY (21.5 % T) strategy, p = 0.065.

Relative timing of muscle activity

Table 1 provides the cross-correlation results, ordered in respective activation sequences for the two steer strategies. Figure 5 is an example of a slalom set from each steer condition to illustrate phasing between muscle bursts and motorcycle roll kinematics.

For simplicity, 3 key muscles - right AD, left ES and left VM - were chosen to test for differences in muscle timing relative to movement cycles depending on the steer strategy. Results are provided in Table 2. A difference in muscle phasing was confirmed only for the lES. Both rAD and lVM showed equivalent phasing relative to roll angular velocity, with all being around one half cycle out of phase (in other words, approximately in phase with left roll velocity peak) regardless of steer strategy. However, steer strategy had an effect on relative onset time for rAD (~24%T earlier in the cycle in ARM trials) and lES (~6%T earlier in the cycle in BODY trials). Burst duration in the ES was not found to be different, although looking at the example in Fig. 4 for the ARM condition, the pattern shows a high frequency modulation that alters the overall shape of the burst, indicating that the similarity of duration does not reflect functional differences. Burst durations were different, however for rAD, being ~20% longer in the BODY condition, as well as for the lVM, being roughly 42% longer in the BODY condition.

Fig. 4 Determination of onsets and offsets for 3 key muscles. The pink dashed lines on the EMG traces indicate the amplitude thresholds used to determine burst onsets and offsets, indicated by green and red stars, respectively. The burst durations for each cycle were then plotted as bars across the associated half cycle of the roll velocity signal. Note the differences between steering strategies in terms of EMG amplitudes, burst durations, and clarity/regularity of periodic activity.

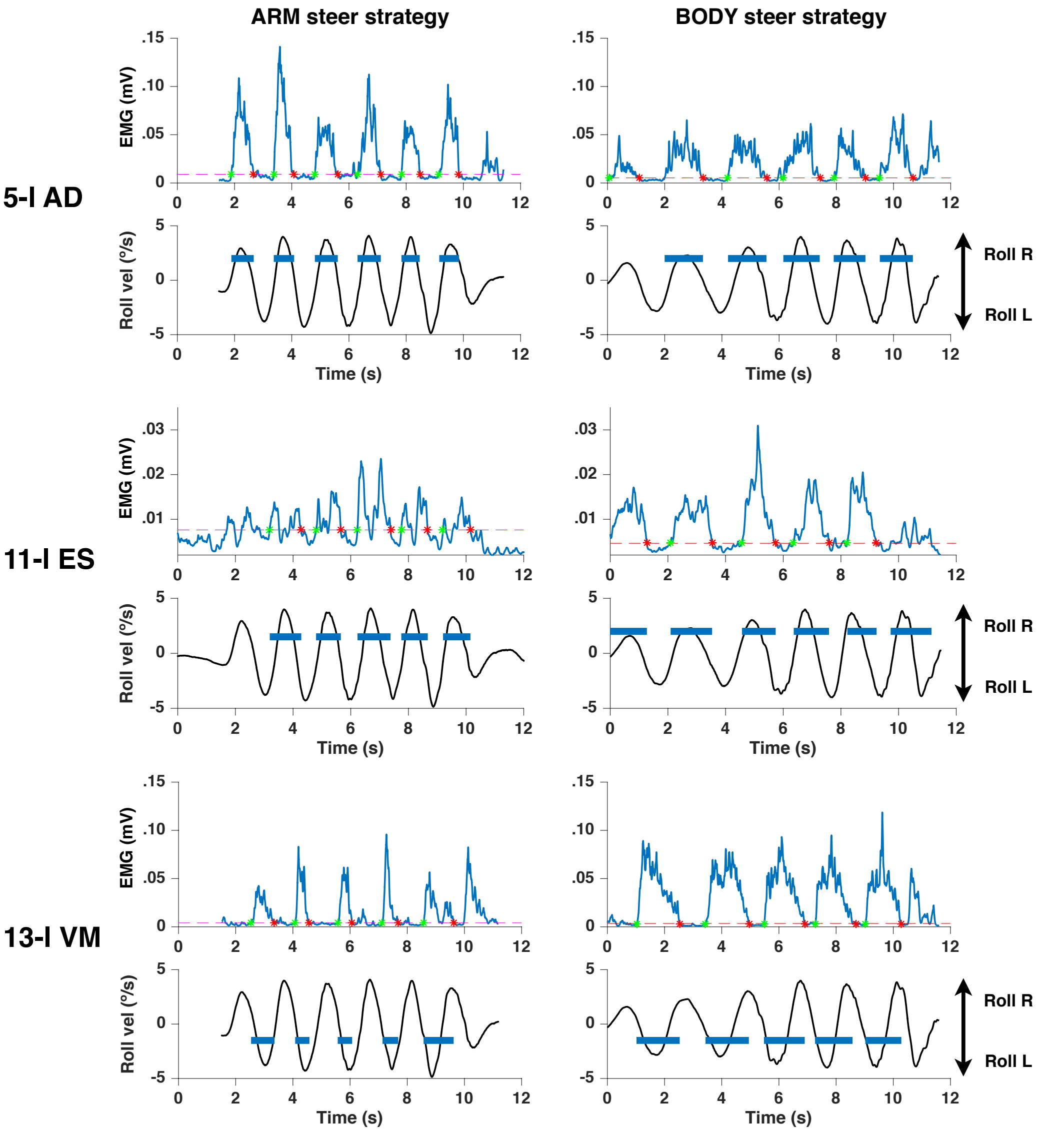


Table 1 Results of cross correlations between muscle signals and angular velocity.

	ARMS		BODY		
	Muscle	Lag%T	Lag%T	*Muscle*	
Yaw L	12-rESL3	21			
	Yaw vel	***20***	***22***	***Yaw vel***	
	4-rBI	5			
Roll R	5-lAD	3	4	5-lAD	Roll R
	Roll vel	***0***	***0***	***Roll vel***	
			-0	4-rBI	Roll R
			-1	2-rBR	Roll R
	8-rTrLo	-8	-12	11-lESL3	Roll R
	15-rTrLa	-10	-14	14-rVM	Roll R
	10-rTrM	-16	-33	1-lBR	
	11-lESL3	-23	-37	6-rAD	
Roll L	13-lVM	-46	-49	13-lVM	Roll L
Roll L	1-lBR	-49			
Roll L	6-rAD	-49			
Roll L	7-lTrLo	-50			
Roll L	9-lTrM	-54	-55	12-rESL3	Roll L

Mean lags are given as percentages of median cycle duration (Lag%T). Roll velocity was used as the reference signal 0, thus positive values indicate muscle peak amplitude before roll peak and negative values indicate muscle peak amplitude after roll peak.

Table 2 Results of statistical tests on muscle timing relative to movement cycles.

Strategy	ARMS		BODY				
Muscle *Variable*	*Mean*	*SD*	*Mean*	*SD*	*p*	*z*	*Mean diff*
6-rAD							
Onset%T	24.9	13.7	1.4	9.4	**<.001**	6.57	23.5
Dur%T	48.5	16.0	68.7	10.9	**<.001**	-5.78	-20.2
Lag%T	-49.1	11.5	-36.7	14.8	0.082		
11-lES							
Onset%T	-26.1	9.3	-20.0	9.4	**.002**	-3.04	-6.1
Dur%T	65.9	12.5	64.0	16.4	.254	1.14	
Lag%T	-22.6	2.6	-12.1	3.6	**<.001**		-10.4
13-lVM							
Onset%T	-72.1	5.5	-73.3	6.8	.176	1.35	
Dur%T	34.1	12.1	76.8	9.3	**<.001**	-8.20	-42.7
Lag%T	-46.4	7.5	-49.4	4.2	.173		

Conclusions

This pilot study explored the use of muscle activation patterns to identify and differentiate between motorcycle rider steering control strategies. Specifically, we compared data from trials in which the rider attempted to use either only arm or only body mechanical inputs to perform sequences of free slalom maneuvers. Relative timing among muscles and between muscles and vehicle roll angular velocity were compared to assess differences in rider coordination of the steer task.

Hypothesis 1 (each steer strategy requires a different muscle activation pattern) was confirmed with the identification of differences in muscle phase sequences and observation of differences in the shapes and frequency modulation of the EMG traces. Key muscles associated with the direction changes were evident from the strong periodic patterns, and secondary muscles having more irregular or continuous activity. For this rider, the muscles that appeared to produce the key activity related to the ARM steer strategy were the anterior deltoid, and all of the triceps locations. These observations are consistent with the expectation of the strategy being dominated by arm pushing actions. Interestingly, the left knee extensor also showed consistently periodic activity, but not the right. Such asymmetries may be reflect individual idiosyncrasies in riding style, which can potentially complicate analyses. For the BODY steer strategy, the lumbar spine extensors and knee extensors were very clearly active in producing the slalom pattern, as was expected. The AD was also very clearly active, but what is unknown is whether their activation was related to initiation of the direction changes or rather reflect a postural function in support of body weight distribution changes as a result of motorcycle lean angle. In general, for the BODY trials the elbow extensors showed much less clear periodic activity: what appears irregular periodic bursting modulated by a noisy baseline activity, is likely indicative of an ongoing activation related more to joint stabilization as force is transferred from the trunk to the handlebars.

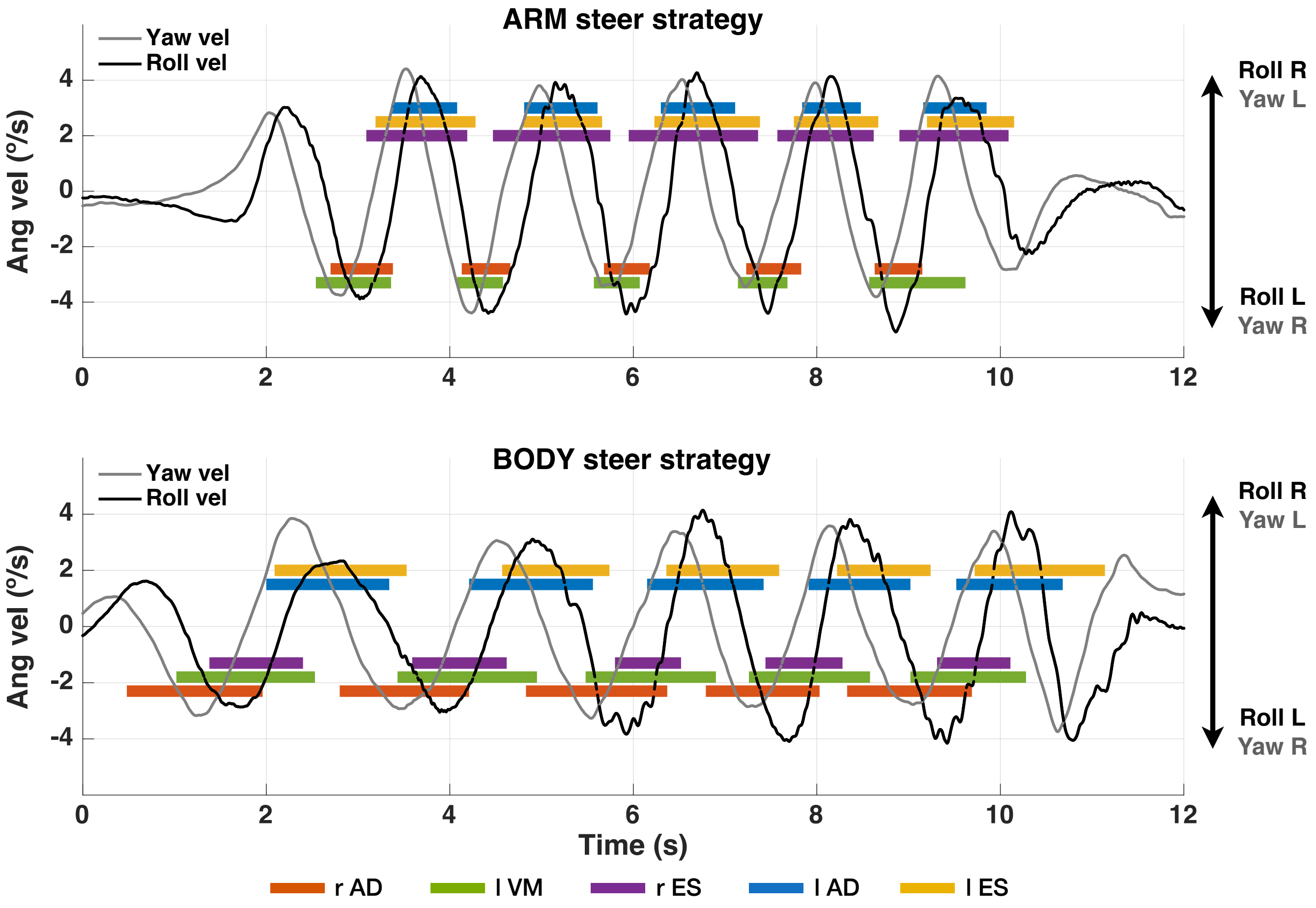


FIG. 5 Examples of muscle phasing from individual trials.

Hypothesis 2 was confirmed by differences in relative onset times between the steer conditions, as well as in burst durations. In particular, the left lumbar ES was in phase with roll velocity to the right in the BODY strategy. This is likely explained as the left spine lateral flexor first becoming active eccentrically towards the end of roll right to reduce roll velocity and then contract eccentrically to reverse direction, initiating leftward roll. The right knee extensor was also in phase with right roll, coherent with the transfer of weight to the right foot peg during right lean, or pushing against the peg to induce roll.

In contrast, in the ARM strategy, the lumbar right ES appeared to be in-phase with left yaw velocity, 20%T earlier than roll angle, and more closely related in time with steer angle. This finding is consistent with a counter steering approach which results first in a transient rotation of the front wheel around the steer axis in the opposite direction to the curve, followed by inward leaning of the motorcycle. Both left and right signals were very noisy, likely being more involved in postural mediation to facilitate arm actions and respond to roll changes, rather being active to motivate direction changes.

In both steer strategies, AD muscles were in phase with roll velocity peaks in the opposite direction. As with the ES in the BODY strategy, this is coherent with the blending of antagonistic and agonistic function of an muscle during movement oscillating to first slow down the motion and then accelerate the segment in the opposite direction. This similarity may relate to a phase-locked role of the AD that is specified by the biomechanics of the system (e.g. weight/postural support) at the time of peak roll, and not by voluntary intention.

AD onset was earlier in the movement cycle in ARM trials whereas ES onsets were earlier in the BODY strategy. ES burst durations were not different between steer strategies but the shape of the patterns suggest very different functions, that is the ES clearly motivate roll in the BODY strategy while in the ARM trials they seem to have a more postural/adaptive function. In the BODY trials, the longer burst durations for AD, ES and VM, together with the very strong periodic bursting seem to be coherent with the need to overcome the high inertia of the PTW in creating direction changes by changing vehicle roll angle without the aid of counter steering. This combined with the finding of significantly shorter cycle duration for the ARM steer strategy provides evidence to support the claim that steering using voluntary application of counter steer inputs to the handlebars is a quicker, more efficient steer strategy. The fact that relative timing of peak activity of the AD muscles with respect to roll velocity was the same regardless of steer strategy, provides further evidence that counter steer inputs may be produced simply thorugh rider-PTW mechanical coupling even if a rider believes they are steering by leaning or pushing against the foot pegs.

Future analyses are can address some of these questions by comparing muscle timing patterns against measured pressure inputs to the vehicle, and vehicle roll and steer angle changes. Future studies will be needed to confirm the generality of muscle timing patterns across other riders.

Importantly, we have demonstrated that it is possible to distinguish between voluntarily selected steering strategies based on the muscle activation patterns, as this cannot be confirmed by vehicle outcome measures alone. Thus EMG can be used to identify different steering strategies to better understand rider-motorcycle control interaction in lateral control. Specifically, we now have confirmation for the assumption that there are different ways to produce direction changes, which is not evident from visual observation or vehicle data analysis alone. Additionally, using EMG we can confirm whether or not a test rider has succeeded in following instructions to implement one or another steering strategy, which can aid interpretation of vehicle outcome data in future steer control and bend-following studies.

Acknowledgements

Funds for this pilot study were provided by the COST Action TU1407 Safe2wheelers. Thank you to Stéphane Espié, Samir Bouaziz and the research group at The IFSTTAR lab Digiteo 660, University Gustave Eiffel SATIE, MOSS premisse for their collaboration and to University of Florence MOVING group for support and instrumentation.

References

De la Barrera EJ, and Milner TE. The effects of skinfold thickness on the selectivity of surface EMG. *Electroencephalogr Clin Neurophysiol* 93: 91-99, 1994.

Delsys. Delsys Wearable Sensors for Movement Sciences https://www.delsys.com/trigno/research/#trigno-avanti-sensor.

Hermens HJ, Freriks B, Disselhorst-Klug C, and Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology* 10: 361-374, 2000.

Kamen G, and Gabriel D. *Essentials of electromyography*. Human kinetics, 2010.

Loiseau P, Boultifat CNE, Chevrel P, Claveau F, Espié S, and Mars F. Rider model identification: neural networks and quasi-LPV models. In: IET Intelligent Transport SystemsInstitution of Engineering and Technology, 2020.

Nugent MM, and Milner TE. Segmental specificity in belly dance mimics primal trunk locomotor patterns. *Journal of Neurophysiology* 117: 1100-1111, 2017.

Nugent MM, Stapley PJ, and Milner TE. Independent activation in adjacent lumbar extensor muscle compartments. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 22: 531-539, 2012.

VIROLO++ Study of bend-taking behaviour of motorbike riders application to training and intelligent transport systems. http://www.virolo2plus.universite-paris-saclay.fr/.