Quantifying the hip-ankle synergy in short-term maximal cycling

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Abstract

Simulation studies have demonstrated that the hip and ankle joints form a task-specific synergy during the downstroke in maximal cycling to enable the power produced by the hip extensor muscles to be transferred to the crank. The existence of the hip-ankle synergy has not been investigated experimentally. Therefore, we sought to apply a modified vector coding technique to quantify the strength of the hip-ankle moment synergy in the downstroke during short-term maximal cycling at a pedalling rate of 135 rpm. Twelve track sprint cyclists performed 3 x 4 s seated sprints at 135 rpm, interspersed with 2 x 4 s seated sprints at 60 rpm on an isokinetic ergometer. Data from the 60 rpm sprints were not analysed in this study. Joint moments were calculated via inverse dynamics, using pedal forces and limb kinematics. The hip-ankle moment synergy was quantified using a modified vector coding method. Results showed, for 28.8% of the downstroke the hip and ankle moments were in-phase, demonstrating the hip and ankle joints tend to work in synergy in the downstroke, providing some support findings from simulation studies of cycling. At a pedalling rate of 135 rpm the hip-phase was most frequent (42.5%) significantly differing from the in- ($P = 0.044$), anti- ($P < 0.001$), and ankle-phases ($P = 0.004$), demonstrating hip-dominant action. We believe this method shows promise to answer research questions on the relative strength of the hip-ankle synergy between different cycling conditions (e.g., power output and pedalling rates).

Keywords: joint moments**,** movement coordination, sprint cycling, vector coding.

1 Introduction

The goal of short-term maximal cycling is to maximise mechanical power output delivered to the crank (van Soest & Casius, 2000). To achieve this, muscle and joint actions need to be coordinated to facilitate energy transfer from muscles through body segments to deliver

maximum effective crank force (Raasch et al., 1997). Uni-articular hip and knee extensor muscles (gluteus maximus and vastii) are the primary power producers in maximal cycling (Dorel et al., 2012; Martin & Nichols, 2018; Raasch et al., 1997; van Ingen Schenau et al., 1992). Simulation studies have demonstrated that hip extensor muscles (gluteus maximus) produce energy in the downstroke which is transferred to the limb (Fregly & Zajac, 1996; Raasch et al., 1997). Additionally, ankle plantar-flexor muscles (gastrocnemius and soleus) need to be co-excited with hip extensors to form a synergy to transfer this energy to the crank (Dorel et al., 2012; Raasch et al., 1997). Without this co-excitation, simulations indicate that energy produced by the hip extensors would simply accelerate limbs (dorsiflexing the ankle and hyperextending the knee), rather than being transferred into effective crank force (Raasch et al., 1997). Whereas, the knee extensors (vastii) are able to transfer most of the energy they generate directly to the crank (Raasch et al., 1997). Martin and Nichols (2018) provided further evidence for this functional coordination mechanism using simulated work loops. They demonstrated that the ankle has a different role to knee and hip joints in maximal cycling - acting to transfer - instead of maximise muscle power (Martin & Nichols, 2018). However, existence of the hip-ankle synergy has not been verified experimentally. Hence, developing a method to experimentally quantify the strength of this synergy in cycling performance is important.

Vector coding can be used to quantify inter-segment, inter-joint and inter-limb coordination (Bayne, 2020; Chang et al., 2008; Hamill et al., 2000; Wheat & Glazier, 2006). Vector coding can identify and quantify coordination differences between-participants and movements, providing insights into coordination patterns not evident from observing joint or segment angle data alone (Needham et al., 2014; Wheat & Glazier, 2006). Vector coding of joint

moment data could, provide a useful methodology to quantify strength of hip-ankle joint moment synergy in short-term maximal cycling.

This study aimed to apply a vector coding technique to quantify strength of hip-ankle moment synergy in the downstroke during short-term maximal cycling at a pedalling rate of 135 rpm.

2 Methods

2.1 Participants

Twelve competitively experienced track sprint cyclists, at under 23 international level (5), Master's international and national levels (4), or Junior national level (3) participated in this study. Participants were varied in sex, age and anthropometrics (4 males and 8 females, age: 24.1 ± 13.8 yr, body mass: 68.2 ± 11.1 kg, height: 1.70 ± 0.07 m,), but were similar in cycling performance level (flying 200 m personal best: 11.61 ± 0.90 s). Participants were provided with study details and gave written informed consent. The study was approved by the XXXX University XXXX Research Ethics Sub-Committee.

2.2 Experimental protocol

An isokinetic ergometer was set up to replicate each participant's track bicycle position. Riders undertook their typical warm-up on the ergometer at self-selected pedalling rate and resistance for at least 10 minutes, followed by one 4 s familiarisation sprint at 135 rpm. Riders then conducted 3 x 4 s seated sprints at 135 rpm, interspersed with 2 x 4 s seated sprints at 60 rpm on the isokinetic ergometer with 4 minutes recovery between efforts. A pedalling rate of 135 rpm was chosen as this is representative of the pedalling rate during the flying 200 m event in track cycling and within an optimal pedalling rate range for track sprint

cyclists (Dorel et al., 2005; Kordi et al., 2020). Data from the 60 rpm sprints were not analysed in this study.

Isokinetic ergometer

A SRM cycle ergometer frame and flywheel (Julich, Germany) were used to construct an isokinetic ergometer. The modified ergometer flywheel was driven by a 2.2-kW AC induction motor (ABB Ltd, Warrington, UK), controlled by a frequency inverter equipped with a braking resistor (Model: Altivar ATV312 HU22, Schneider Electric Ltd, London, UK) (Burnie et al., 2020). This set-up enabled participants to start their bouts at the target pedalling rate, rather than expending energy in accelerating the flywheel. The ergometer was fitted with force pedals (Model ICS4, Sensix, Poitiers, France) and crank encoder (Model LM13, RLS, Komenda, Slovenia), sampling data at 200 Hz.

2.3 Kinematic and kinetic data acquisition

Two-dimensional kinematic data of each participant's left side were recorded using a 100 Hz video camera with infra-red ring lights (Model: UI-522xRE-M, IDS, Obersulm, Germany) (Burnie et al., 2020). Reflective markers were placed on the pedal spindle, lateral malleolus, lateral femoral condyle and greater trochanter. Kinematics and kinetics on the ergometer were recorded by CrankCam software (CSER, SHU, Sheffield, UK), which synchronised the camera and pedal force data and was used for data processing (Burnie et al., 2020).

2.4 Data processing

All kinetic and kinematic data were filtered using a Butterworth fourth order (zero lag) low pass filter with a cut off frequency of 14 Hz. Instantaneous left crank power was calculated from the product of the left crank torque and crank angular velocity. The average left crank

power was calculated by averaging the instantaneous left crank power over a complete pedal revolution. Joint moments were calculated via inverse dynamics (Elftman, 1939), using pedal forces, limb kinematics, and body segment parameters (de Leva, 1996). Joint extension moments were defined as positive.

Data were analysed using a custom Matlab (R2017a, MathWorks, Cambridge, UK) script. Each sprint lasted for 4 s, providing six complete crank revolutions. Joint moments were resampled to 100 data points around the crank cycle and the mean value at each time point was calculated to obtain a single ensemble-averaged time series for each trial. Owing to technical problems for two participants only data from two instead of three sprints was collected.

Quantifying hip-ankle joint synergy

To quantify hip-ankle joint coordination and strength of the hip-ankle joint synergy a vector coding method was applied to joint moment-moment diagrams (Chang et al., 2008). These were selected as the most appropriate variables to evidence if net hip and ankle joint moments act in synergy during the downstroke (Fregly & Zajac, 1996). Coupling angles (γ_i) were calculated from hip-ankle moment diagrams (Figure 1) for each crank cycle data point for all revolutions of each participant's sprints (Chang et al., 2008). The coupling angle is defined as the orientation of the vector (relative to the right horizontal) between two adjacent points on the moment-moment plot, Figure 2. Since coupling angles are directional in nature, mean coupling angles were computed using circular statistics (Batschelet, 1981).

Mean coupling angles for each participant were categorised into four coordination phases: in-phase, anti-phase, hip-phase and ankle-phase based on proposals of Chang et al. (2008) (Figure 2). When coupling angle values are 45° and 225° (a positive diagonal), the

components are in-phase: both hip and ankle moments are increasing or decreasing at similar rates, i.e., hip and ankle joints are working in synergically (Arnold et al., 2017). Conversely, when coupling angles are 135° and 315° (a negative diagonal), components are anti-phase. For example, when hip moments are increasing whilst ankle moment are decreasing. When coupling angles are parallel to the horizontal (0° and 180°), ankle moments are changing but not hip moments – ankle-phase. When coupling angles are parallel to the vertical (90° and 270°), hip moments are changing but not ankle moments – hip-phase. Since coupling angles rarely lie precisely on these angles, the unit circle was split into 45° bins used by Chang et al. (2008) (Figure 2). Frequencies within which mean coupling angles lay in these coordination patterns, during the downstroke (defined between crank angles of 0 to 180°) were calculated for each participant, using the following equation: Frequency of coordination phase (%) = (Number of occurrences of coordination phase/51) × 100, (note there are 51 data points in the downstroke). This process was repeated to calculate group mean coupling angles for sprints at 135 rpm and coupling angle variability was calculated according to Needham et al. (2014) (Figure 3). Strength of the hip-ankle synergy was quantified by the frequency of in-phase coordination pattern between hip and ankle moments in the downstroke.

2.5 Statistical analysis

Differences between frequencies of coordination phases were assessed using a Friedman test with post-hoc Wilcoxon matched pairs using IBM SPSS Statistics Version 28 (IBM UK Ltd, Portsmouth, UK).

3 Results

Average left crank power over a complete revolution for sprints at 135 rpm was 494.1 ± 91.2 W. Hip and ankle moments were in-phase for 28.8% of the downstroke, with the hip-phase

the most frequent coordination phase (42.5%) (Figure 4). A Friedman test ($\chi^2 = 19.3$, $P < 0.0005$) indicated that coordination phase frequencies differed across the four coordination phases. Post-hoc Wilcoxon matched pairs indicated that in-phase was significantly different to anti-phase ($P = 0.004$), hip-phase ($P = 0.044$) and ankle-phase ($P = 0.017$). Hip-phase was significantly different to the anti-phase ($P < 0.001$), and ankle-phase ($P = 0.004$).

4 Discussion

We demonstrated that a vector coding method can be used to quantify strength of hip-ankle joint moment synergy during the downstroke in cycling. Data imply a tendency for hip and ankle joints to work in synergy in the downstroke during short-term maximal cycling at a pedalling rate of 135 rpm.

The evidence of in-phase coordination between the hip and ankle joints in the downstroke at 135 rpm, provides some support for the simulation studies suggesting that hip and ankle joints need to work in synergy to transfer energy produced by hip extensors to the crank (Fregly & Zajac, 1996; Raasch et al., 1997). Fregly and Zajac (1996) modelled steady state pedalling at 75 rpm and Raasch et al. (1997) modelled the acceleration phase with pedalling rate increasing from 80 to 120 rpm through a revolution. Our results suggest that the hip-ankle synergy may not be as strong at pedalling rates higher than previously modelled. A key factor that could influence the strength of the hip-ankle synergy is the time available in the downstroke to coordinate joint actions. At 75 rpm the downstroke lasts 0.40 seconds (pedalling rate used in Fregly and Zajac (1996) study), compared to 0.22 seconds at 135 rpm. Therefore, this suggests as the task complexity increases (e.g., due to changes in pedalling rate from 75 to 135 rpm), strength of hip-ankle synergy reduces, implying it is more challenging to coordinate joint moments at higher pedalling rates. This observation supports

previous findings suggesting that, as task complexity increases, differences in coordination and coordination variability emerge (Weir et al., 2019).

At a pedalling rate of 135 rpm, the hip-phase is the most frequent coordination phase in the downstroke suggesting that sprints at 135 rpm display a hip-dominant coordination pattern. A much greater contribution from hip extension power to crank power at higher pedalling rates has been observed, identifying the optimal pedalling rate for maximum hip extension power was around 150 rpm, whereas the optimal pedalling rate for knee extension and flexion power was lower (McDaniel et al., 2014). Our finding that hip-phase coordination is dominant at higher pedalling rate supports and expands upon the notion that the role of the hip becomes more important at higher pedalling rates, from a power production and coordination perspective.

This study demonstrated the application of vector coding to quantify hip-ankle moment synergy in maximal cycling. Further research is required to investigate the presence of hip-ankle moment synergy in the downstroke at different pedalling rates and power outputs.

5 Conclusion

A modified vector coding technique can be used to quantify the strength of the hip-ankle moment synergy in the downstroke during cycling. Hip and ankle joints tend to work in synergy in the downstroke during short-term maximal cycling, providing some support for findings of previous cycling simulation studies. This method could potentially be used to assess cyclists' pedalling techniques and to monitor effect of training or equipment interventions on coordination patterns.

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7 Figure legends

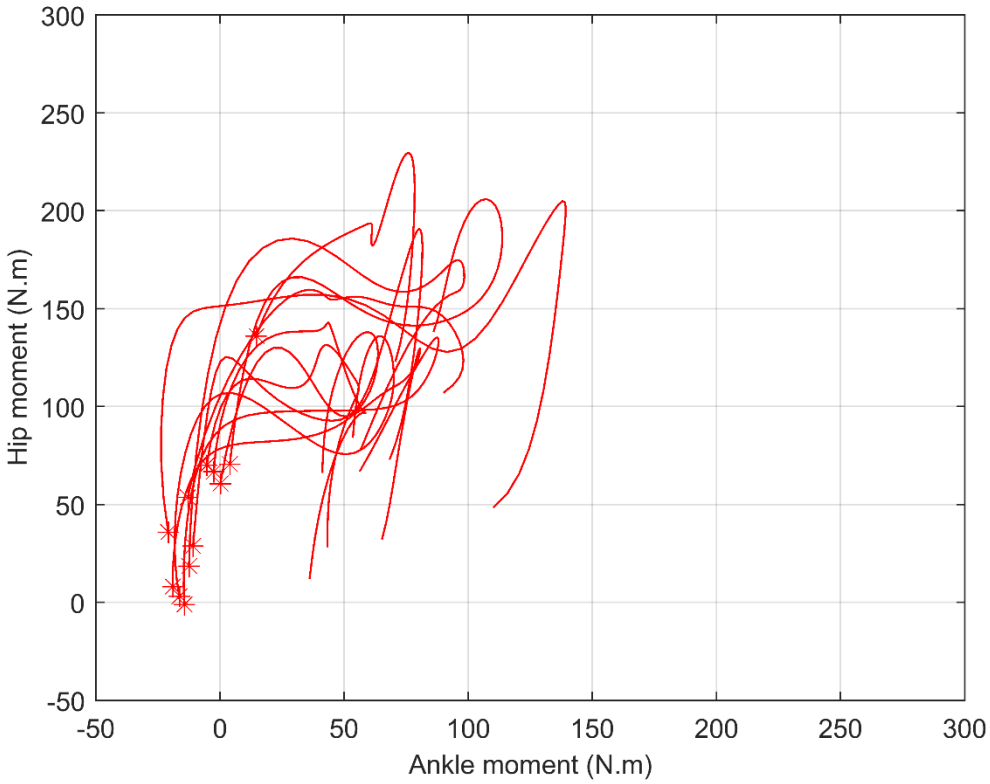
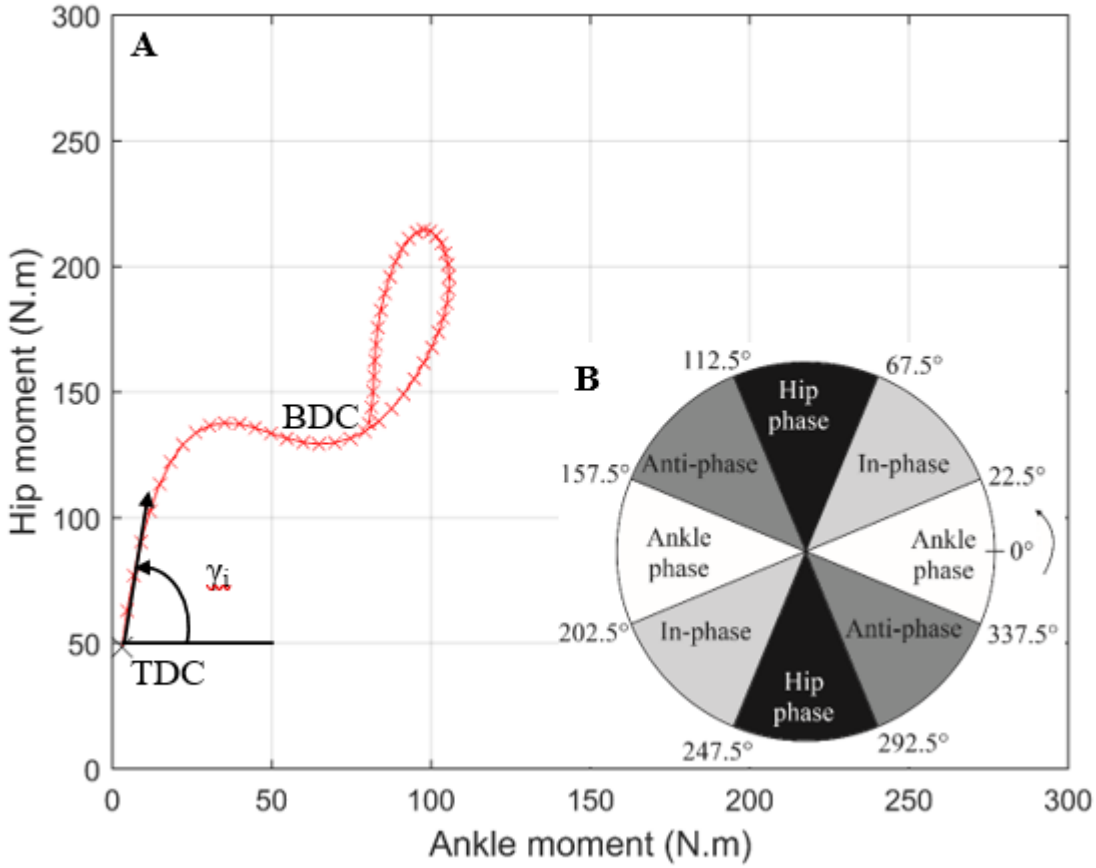


Figure 1: Mean hip-ankle moment plots for sprints at 135 rpm for the downstroke for each participant, with * indicating top dead centre (TDC).



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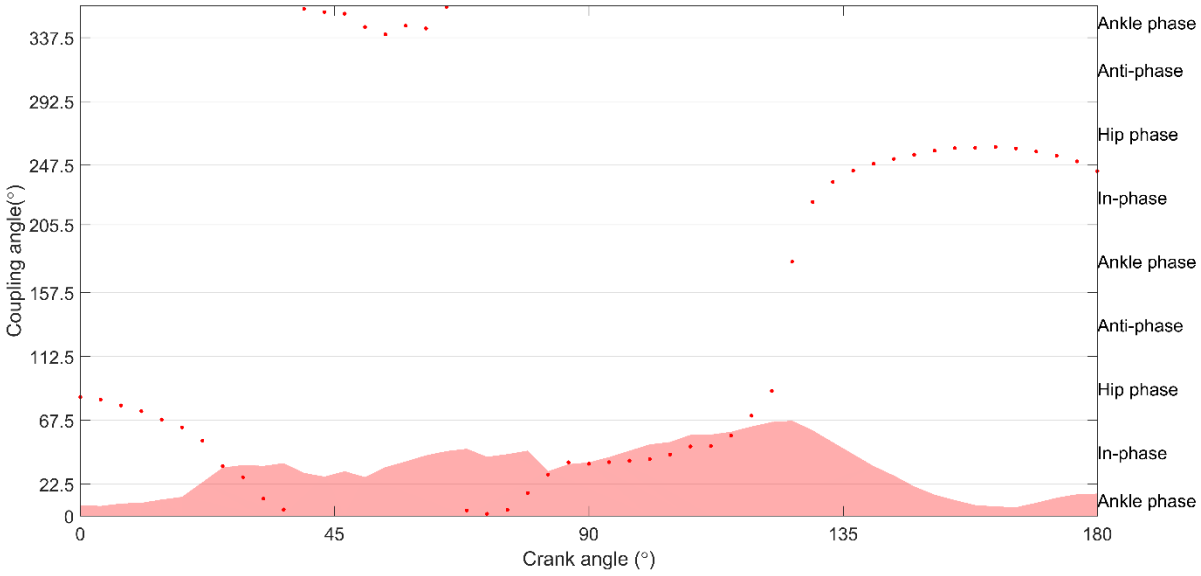
253 **Figure 2: A: An illustration of the calculation for a coupling angle (γ_i) from hip-ankle**
254 **moment plot (one downstroke during a sprint). Top dead centre (TDC) = 0°, and**
255 **bottom dead centre (BDC) = 180°. B: The coordination pattern classification system for**
256 **the coupling angle (γ_i)**



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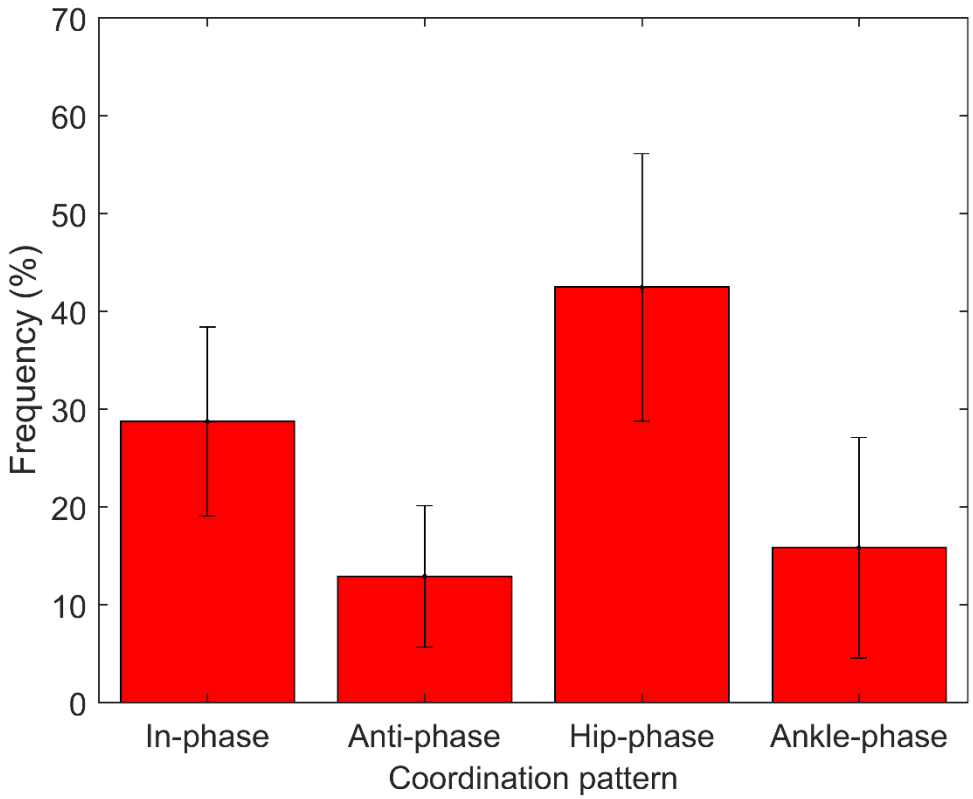
258 **Figure 3: Mean coupling angle for hip-ankle moments for sprints at 135 rpm for the**
259 **downstroke. Shaded area represents coupling angle variability.**



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261 **Figure 4: Hip-ankle moment coordination patterns during downstroke phase of the**
262 **crank cycle for sprints at 135 rpm.**