INFLUENCE OF BODY SEGMENT INERTIA PARAMETERS ON UNCERTAINTIES IN JOINT SPECIFIC POWER DURING SPRINT CYCLING: A MONTE CARLO SIMULATION

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Joint-specific power analyses are important in the assessment of cycling biomechanics but they contain uncertainties due to errors in input parameters. The aim of the study was to investigate the effect of uncertainty in body segment parameters on joint-specific powers during maximal sprint cycling, using a Monte Carlo analysis. Joint powers were estimated using standard inverse dynamics techniques, with body segment parameters and uncertainty in these inputs defined using reference data. Monte Carlo simulations (10,000 iterations) were performed for pedal cycles at 120 rpm and 160 rpm. The analysis highlighted practically relevant uncertainties in peak hip joint power at race-specific pedalling rates caused by uncertainty in body segment parameters.

KEYWORDS: inverse dynamics, mass, moment of inertia, centre of mass.

INTRODUCTION: A joint-specific analysis of cycling power provides insight into movement strategies that are not apparent when observing pedal power alone. Such analyses have described the movement strategy alterations occurring in response to, for example, changes in pedal power output, pedalling rate, and several bicycle setup parameters (Broker and Gregor, 1993, Bini et al. 2010, Elmer et al., 2011).
Standard inverse dynamics techniques can be used to estimate joint-specific power. For this purpose, the required body segment parameter (BSIP) data are typically taken from reference data sets (Elmer et al., 2011). Differences between reference and real values for an individual cause uncertainty in the inverse dynamics calculation, although the extent to which this affects joint specific power in cycling is not known. This issue might have particular relevance to maximal sprint cycling as pedalling rates can reach up to 160 rpm during competitive races (Dorel et al., 2005). Under these pedalling conditions, the effects of uncertainties in the inertial terms are likely to be exaggerated due to high segment accelerations. This highlights the potential importance of uncertainties in body segment parameters on uncertainties in joint-specific power during maximal sprint cycling.
Several approaches can be used to examine uncertainty in output parameters caused by the uncertainty in inputs to a model. Basic sensitivity analyses provide a measure of how error in an input parameter impacts the model result. However, they are generally limited to few input parameters/perturbations and it can be difficult to account for all combinations of errors. More complex uncertainty analyses consider the uncertainty in all inputs, identifying how they contribute to the total uncertainty in the output. The Taylor Series Method (TSM) allows uncertainty in all inputs to be considered but, as the uncertainty in inputs are considered to be random and uncorrelated, the results represent an upper bound of uncertainty (Reimer et al., 2008). Like TSM, probabilistic analyses such as the Monte Carlo method provide comprehensive techniques to simultaneously assess the impact of uncertainties that arise from multiple inputs. Across thousands of iterations, inputs are randomly generated from pre-determined probability distributions (based on baseline values and estimated uncertainty), resulting in distributions of output parameters which characterise uncertainty. The aim of this study was to investigate the effect of uncertainty in body segment parameters on joint-specific powers during maximal sprint cycling, using a Monte Carlo analysis.

METHOD: Raw data for the Monte Carlo analysis were taken from a larger study for which institutional ethical approval was obtained. Data for a single male participant (mass 80 kg) completing a single bout of maximal effort (10 s) isokinetic ergometer cycling in two cadence conditions were used - 120 rpm and 160 rpm. Pedal force data were obtained using instrumented cranks (Factor Cranks, BF1 Systems, Diss, UK) sampling at 100 Hz, with pedal

reaction forces resolved into the laboratory coordinate system (vertical and horizontal components). Kinematic data were obtained using a single infra-red machine vision camera (IDS, Obersulm, Germany) – with an infra-red light source - sampling at 100 Hz. The camera was positioned perpendicular to the sagittal plane of the participant at a height of approximately 1 m and approximately 3 m from the measurement plane.
The two dimensional coordinates of five retro-reflective spherical markers – attached the pedal spindle in addition to the lateral malleolus, lateral femoral epicondyle, greater trochanter and iliac crest of the participant – were obtained using standard computer vision and linear scaling techniques. Raw marker and pedal force data were filtered using a fourth order, zero-lag, low-pass Butterworth digital filter (cutoff frequency: 8 Hz for 120 rpm, 11 Hz for 160 rpm). Linear and angular velocities and accelerations were calculated using finite difference techniques and the mass, centre of mass position and moment of inertia of body segments were estimated using reference data (De Leva et al., 1996). Joint reaction forces and net joint moments were calculated at the ankle, knee and hip using standard inverse dynamics techniques. Joint powers at the ankle, knee and hip were determined by taking the product of the net joint moment and joint angular velocity. The scalar product of the hip joint reaction force and linear velocity vectors was calculated to determine the power transferred across the hip joint (hip transfer power: Broker and Gregor, 1993). Power data were interpolated to 100 data points with the first data point at a crank angle of 0 degrees ('top dead centre').
Monte Carlo simulation methods were used to determine the effect of uncertainty in body segment parameters on the uncertainty in ankle, knee and hip joint powers and hip transfer power. A simulation was performed for both the 120 rpm and 160 rpm conditions. Each simulation comprised 10,000 iterations, with perturbations for the input BSIPs on each iteration sampled from Gaussian distributions. The uncertainty (variability in the Gaussian input distribution) in each body segment parameter input was defined using data presented by Nguyen et al. (2014). Similar to Myers et al. (2014), uncertainty in the outputs (ankle, knee, hip joint power and hip transfer power) was expressed by calculating the 5-95% confidence bounds at each time point. Sensitivity of the output parameters to each of the BSIPs was assessed by performing Pearson Product-Moment correlations between the values of a BSIP input and the generated values of an output parameter, at each time point (Myers et al., 2014).

RESULTS: Uncertainties in ankle and knee joint powers were small and - for brevity - are not presented. Uncertainties in hip joint power and hip transfer power were generally greater at 160 rpm than 120 rpm (Figure 1). The magnitude of uncertainty (size of the 5-95% confidence bounds) varied throughout the pedal cycle, with clear periods of greater uncertainty, especially in the 160 rpm condition (Figure 1). Similarly, the sensitivity of the output powers to the input BSIPs, varied throughout the pedal cycle. For example, in the middle of the pedal cycle, hip joint power was more sensitive to thigh mass than lower leg and foot mass (Figure 2). However, during periods at the start and end of the pedal cycle, the relative sensitivity of hip joint power to lower leg was high (Figure 2).

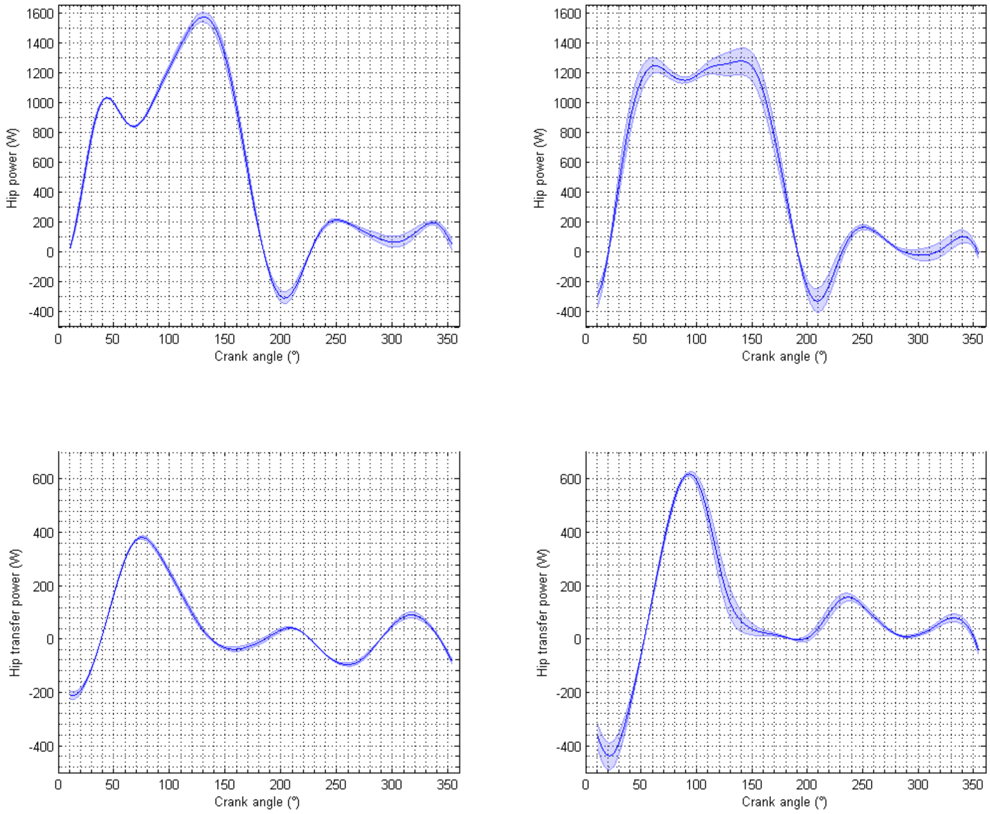

Figure 1. Power versus crank angle and the uncertainties from the Monte Carlo simulation. Left: 120 rpm, Right: 160 rpm. Top: Hip joint power, Bottom: Hip transfer power. Crank angles of 0° and 360° represent top dead centre. Shaded regions: 5-95% confidence bounds from 10,000 iterations of the Monte Carlo simulation

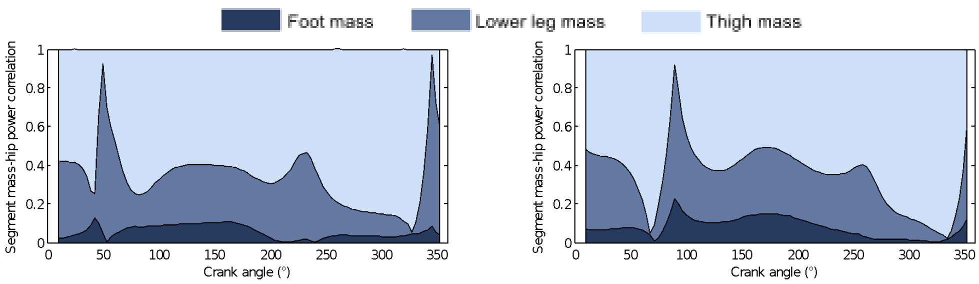

Figure 2. Relative sensitivity (segment correlation coefficient divided by the sum of the segment correlation coefficients) of hip joint power to foot, lower leg and thigh mass. Left: 120 rpm, Right: 160 rpm

DISCUSSION: The aim of this study was to investigate the uncertainty in joint specific power caused by uncertainty in BSIPs during maximal sprint cycling. Uncertainties in ankle and knee joint power were small but uncertainty in hip joint power and hip transfer power was not negligible. Further, uncertainties were greater in the 160 rpm than the 120 rpm condition (Figure 1). In gait, the influence of body segment parameter uncertainties on inverse dynamics calculations during walking are relatively small, especially during the stance phase (Myers et al., 2014). However, the influence is greater during the swing phase (Myers et al., 2014), related to absence of ground reaction forces and greater contribution of the inertial component of the inverse dynamics equations. Likewise, although at 120 rpm uncertainties in hip joint power and hip transfer power are relatively small, at 160 rpm - where the effect of uncertainties in the inertial terms are likely to be exaggerated due to the high segment accelerations - uncertainties in hip joint power are larger. At 160 rpm, 5-95 % confidence bounds were approximately 10% of the magnitude of peak hip joint power. Uncertainties in hip joint power would thus likely have practical relevance when analysing peak hip joint powers at race-specific pedalling rates.

Interestingly, the relative sensitivity of hip joint power to uncertainty in each of the body segment parameters varied through the pedal cycle (Figure 2). For example, hip joint power was most sensitive to uncertainty in thigh mass during most of the pedal cycle but there were periods during which hip joint power was most sensitive to lower leg mass uncertainty. Similar findings have been reported in gait, with differences especially apparent between the stance and swing phases (Myers et al., 2014). The varying influence of body segment parameter uncertainty highlights the importance of a detailed understanding of their effects on joint specific power during sprint cycling.

We estimated body segment parameters from reference data sets derived from a normal population (de Leva, 1996). Likewise, data from a normal population were used to define the input probability distributions for each of the body segment parameters (Nyugen et al., 2014). As sprint cyclists exhibit different body morphologies to cyclists in other disciplines and the general population (Mclean and Parker, 1989), it is likely that errors in input parameters will be larger than those defined in the present study. As such, when normal population reference data are used to calculate joint specific power in sprint cyclists, uncertainties in outputs are likely to be larger than reported here. Nonetheless, even with potentially conservative estimates of input uncertainties, our results highlight the importance of accurate estimates of body segment parameters for calculating joint specific power during sprint cycling at high cadences. Further work is required to characterise the body segment parameters of sprint cyclists. Additionally, future research should focus on identifying the effects of other sources of uncertainty - such as skin movement artefact and pedal force measurement errors - on uncertainties in joint specific power.

CONCLUSION: Uncertainties in lower extremity body segment parameters produce practically relevant uncertainty in peak hip joint powers during maximal sprint cycling at race-specific pedalling rates.

REFERENCES:

Bini, R.B., Tamborindeguy, A.C. and Mota, C.B. (2010). Effects of Saddle Height, Pedalling Cadence, and Workload on Joint Kinetics and Kinematics During Cycling. *Journal of Sport Rehabilitation,* **19***,* 301-314*.*

Broker, J.P.. and Gregor R.J. (1993). Mechanical energy management in cycling:source relations and energy management. *Medicine and Science in Sports and Exercise*, **26**, 64-74

de Leva P. (1996). Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. *Journal of Biomechanics*, **29**,1223–30.

Dorel, S., Hautier, C.A., Rambaud, O., Rouffet, D., Van Praagh, E., Lacour, J.-R. and Bourdin, M. (2005). Torque and Power-Velocity Relationships in Cycling: Relevance to Track Sprtin Performance in World-Class Cyclists. *International Journal of Sports Medicine,* **26***,* 739-746.

Elmer, S. J., Barratt, P. R., Korff, T., and Martin, J. C. (2011). Joint-specific power production during submaximal and maximal cycling. *Medicine and Science in Sports and Exercise*, **43**, 1940–7.

Myers, C. a, Laz, P. J., Shelburne, K. B., and Davidson, B. S. (2014). A Probabilistic Approach to Quantify the Impact of Uncertainty Propagation in Musculoskeletal Simulations. *Annals of Biomedical Engineering*.

Nguyen, T. C., and Reynolds, K. J. (2014). The effect of variability in body segment parameters on joint moment using Monte Carlo simulations. *Gait & Posture*, **39**, 346–53.

Riemer, R., Hsiao-Wecksler, E. T., and Zhang, X. (2008). Uncertainties in inverse dynamics solutions: a comprehensive analysis and an application to gait. *Gait & Posture*, **27**, 578–88.