LOWER LIMB TRI-JOINT SYNCHRONY DURING RUNNING: A LONGITUDINAL AGE-BASED STUDY

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Cluster Phase analysis was used to examine age-related changes in synchrony between three joints of the lower limb during running stance. Ten male, endurance athletes (Age = 53.54±2.56 years [M50]) participated in the study at baseline (0 years) and then returned for re-testing after seven years (Age = 60.49±2.56 years [M57]). Lower limb coordinate and ground reaction forces were collected as participants performed running trials at a velocity of 3.83±0.40 m/s contacting the force plate with their preferred limb. Statistical parametric mapping identified that the hip, knee and ankle joint synchrony during the stance phase did not change. However tri-joint synchrony was significantly higher at M57 compared to M50 during the absorption sub-phase of stance. The increased joint synchrony as a function of age could be a mechanism associated with this key injury provoking phase.

KEYWORDS: Cluster Phase, Dynamical Systems Theory, Coordination, Kinematics

INTRODUCTION: Biomechanical research exploring the age-based mechanics of running gait can provide valuable insight into the reported decline in master endurance running performance (Tarpenning et al., 2004). Extended insights into age-based biomechanical responses of competitive endurance athletes are warranted particularly above 50 years of age, which is considered a significant catalyst for injury (Taunton et al., 2002).

Most ageing research examining dynamic movements has been cross sectional in nature and focussed on walking (Lilley et al., 2011). A longitudinal design provides a better understanding of age-based changes in running gait by considering individual changes prospectively.

Since it is likely that age induces changes in the kinematics of masters' running gait, but few studies have shown biomechanical differences (Fukuchi et al., 2008), it might be that differences occur in the interaction between joints. A major focus of the dynamical systems approach to motor control is to understand how the components within a system (e.g., joint space degrees of freedom) become coordinated to effectively and efficiently meet task demands (Kelso et al., 1995). To capture whole-body coordination in gait, Segers et al. (2007) described the collective state of the system through phase relations in two biomechanically relevant global variables: kinetic energy and gravitational potential energy. Statistical methods such as Principal Component Analysis have been used to reduce the dimensionality of mechanical degrees of freedom for all body segments (Lamoth et al., 2009), increasing our understanding of the coordination involved in this whole-body task. More recently, Williams and Vicinanza (2017) presented a method to consider the relations between multiple oscillators using frequency decomposition. To date however, no studies have investigated coordination in the three key joints that make up the lower limb.

The aim of this study was to examine tri-joint synchronisation using Cluster Phase analysis. We hypothesised that hip, knee and ankle joint synchrony during the stance phase of gait would improve for competitive athletes after a 7 year period of ageing. Our approach to study the coordination (as simultaneous synchrony) between three joints adapted the Cluster Phase method proposed by Frank and Richardson (2010).The method was based on the Kuramoto order parameter (1984 & 1989), which has been previously used to study synchronisation of many-body systems in life (Walker (1969) for cricket synchronisation) and social sciences (Néda et al. (2000) for synchronised applause).

METHODS: Ground reaction force and coordinate data were collected using a 12 camera Vicon system (sample rate: 100 Hz) synchronised with multiple Kistler force plates (sample rate: 1000 Hz) for ten male endurance-trained athletes (Age = 53.54±2.56 years, Mass = 71.05±7.92 kg [M50]) whilst performing multiple over ground running trials at a horizontal velocity of 3.83±0.40 m/s down a 20 m runway. All athletes provided written informed consent. Ethical approval for the data collection protocol was gained from the host University's Ethics Board prior to study onset. The protocol and data collection was then replicated seven years later (M57).

The Cluster Phase method was used to determine the group average joint synchrony of the sagittal plane ankle, knee and hip joints throughout the stance phase of gait using Frank and Richardson's (2010) adaptation of the Kuramoto order parameter method (1987). The average joint synchrony was reported for the absorption, propulsion and stance phases. If joint synchrony = 1 the movement is in complete tri-joint synchrony.

The Shapiro-Wilk statistical test for normal distribution revealed that all measures were normally distributed. Statistical parametric mapping (SPM) technique with paired t-test was used to examine the differences in the waveform of the group average synchrony for M50 and M57. A paired two-tailed t-test was conducted to examine the differences in average synchrony during the absorption, propulsion and stance phases ($p < 0.05$).

RESULTS: Average joint synchrony measures the presence and magnitude of the tri-joint synchrony. Figure 1 illustrates the group mean tri-joint synchrony for the competitive athletes throughout the stance phase when M50 and seven years later. SPM shows that there were no significant differences in synchrony during stance.

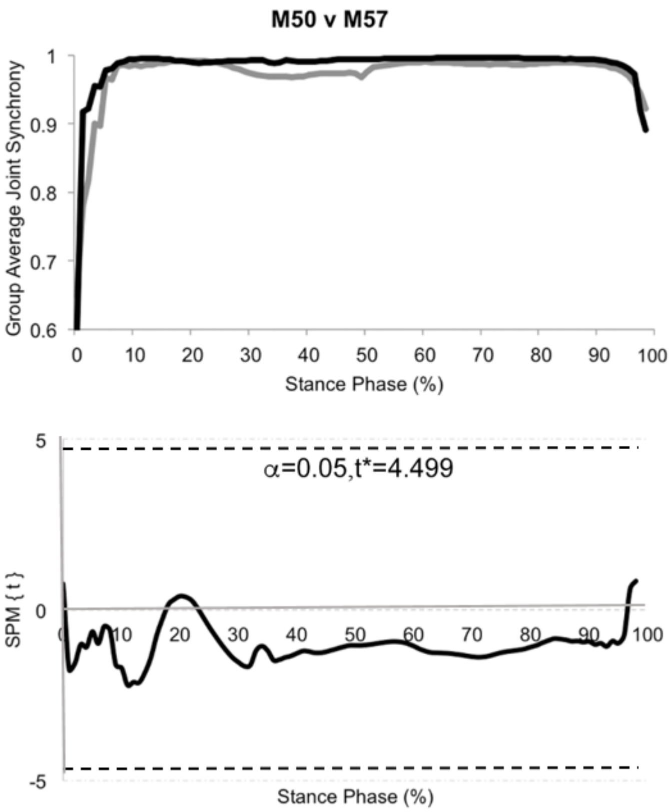

Figure 1: Top: Average joint synchrony for M50 (grey) and M57 (black). Bottom: t-test analysis (SPM {t}) of differences in joint synchrony waveforms for M50 and M57.

Figure 2 illustrates the average synchrony was lower during the absorption sub-phase of stance (BCa 95 % CI [-0.0116, -0.0013], $t(18) = -2.684$, $p = 0.018$, effect size = 0.34), seven years later, as illustrated in Figure 2. Average joint synchrony across the entire stance or the propulsion sub-phase did not change between baseline and testing seven years later.

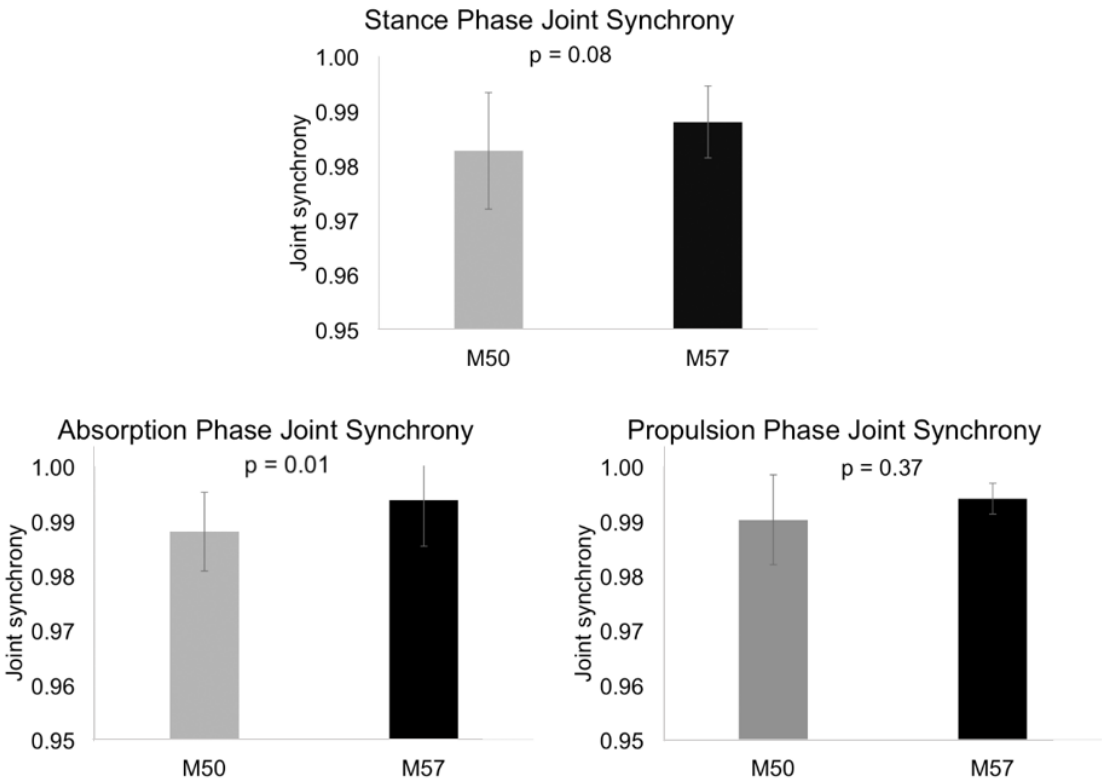

Figure 2: Mean (SD) joint synchrony for M50 (grey) and M57 (black) during the whole stance phase (top), absorption phase (bottom left) and propulsion phase (bottom right).

DISCUSSION: To the authors' knowledge this is the first longitudinal research of changes in the gait mechanics of competitive endurance runners. To further understanding of the organisation of the lower limb movements, Cluster Phase; a novel analysis in this context, was used to examine changes in tri-joint synchrony. It was revealed that joint movements of the lower limb became more synchronous during the absorption sub-phase of stance after ageing seven years.

While previous research has reported more in-phase coupling between the shank and thigh during the braking phase of walking for older adults compared to younger adults (Byrne et al., 2002), the current analysis quantifies synchrony. Synchrony is normally defined through the relative timing of joint movements, in particular, two movements are synchronous if changes are happening at the same time (i.e. simultaneously). However, based on the Hilbert transform, the cluster phase method formalised by Richardson (2010), introduces a new way of describing and characterising synchrony through the relative phases associated with the movement of the multiple individual joints. If the mean relative phase between joints is zero, i.e. the phase of the movement at any time step is equivalent to the cluster phase shifted by a constant, the joints are moving in synchrony.

An increase in tri-joint synchrony in the absorption phase of stance after 7 years indicates that the hip, knee and ankle are working as a coherent single unit where the timings are more similar. The mechanical constraint of increased synchrony that appears to have arisen as a consequence of ageing could be a requirement to attenuate the ground reaction forces since strength has been compromised.

CONCLUSION: An increase in tri-joint synchrony in the absorption sub-phase of stance after 7 years indicates that the hip, knee and ankle are working in unison with an improvement in timing cohesion. The results from this study suggest that the cluster phase method can be used to identify coordination changes in three joints during running as a function of changing biological constraints. Future work could examine whether there is limited adaptability in this synchronisation in response to perturbations in the running surface with ageing, for example. It might also be explored whether increased synchrony is a characteristic of aged gait and movement per se.

REFERENCES

Tarpenning, K., Hamilton-Wessler, M., Wiswell, R. & Hawking, S. (2004). Endurance training delays age of decline in leg strength and muscle morphology. *Medicine and Science in Sports and Exercise*, 36, 74–78.

Taunton, J., Ryan, M. & Clement, D., McKenzie, D., Lloyd-Smith, D. & Zumbo, B. (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, 36, 95-101.

Lilley, K., Dixon, S., & Stiles, V. (2011). A biomechanical comparison of the running gait of mature and young females. *Gait & Posture*, 33, 496-500.

Fukuchi, R. & Duarte, M. (2008). Comparison of three-dimensional lower extremity running kinematics of young adult and elderly runners. *Journal of Sport Sciences,* 26, 1447-54.

Kelso, J. (1995). Dynamic patterns: The self organization of brain and behavior. Cambridge, MA: The MIT Press.

Segers, V., Aerts, P., Lemoir, M., De Clercq, D. (2007). Dynamics of the body centre of mass during actual acceleration across transition speeds. *Journal of Exercise Biology,* 210, 578–585.

Lamoth, C., Beek, P. & Meijer, O. (2002). Pelvis–thorax coordination in the transverse plane during gait. *Gait & Posture*, 16, 101-14.

Williams, G. & Vicinanza, D. (2017). Coordination in gait: Demonstration of a spectral approach. *Journal of Sports Sciences,* 16,1-8.

Frank, T. & Richardson, M. (2010). On a test statistic for the Kuramoto order parameter of synchronization: An illustration for group synchronization during rocking chairs. *Physica D: Nonlinear Phenomena,* 239, 2084-92.

Kuramoto, Y. (1984). Chemical Oscillations, Waves, and Turbulence. Berlin: Springer.

Kuramoto, Y. (1989). Cooperative Dynamics in Complex Physical Systems. Berlin: Springer.

Walker, T. (1969). Acoustic synchrony: two mechanisms in the snowy tree cricket. *Science*, 166, 891-4.

Néda, Z., Ravasz, E., Brechet, Y., Vicsek, T. & Barabási, A. (2000). Physics of rhythmic applause. *Physical Review*, E61, 6987–6992.

Byrne, J., Stergiou, N., Blanke, D., Houser, J., Kurz, M. & Hageman, P. (2002). Comparison of gait patterns between young and elderly women: an examination of coordination. *Perceptual and Motor Skills,* 94, 265-80.

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