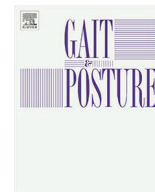




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Gait variability and motor control in patients with knee osteoarthritis as measured by the uncontrolled manifold technique

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ABSTRACT

Knee osteoarthritis (OA) causes pain, reduced muscular strength and stiffness of the affected joint. In response, the motor control mechanism is altered, potentially compromising stability during acts of daily living. Reduced walking stability can be quantified in terms of gait variability. This study therefore aimed to identify and quantify the effects of knee arthritis on gait variability. Fifty adults (25 males/25 females) with end-stage OA of the knee sufficiently symptomatic to require joint replacement, walked on a self-paced treadmill for 2 min. A motion capture system was used to record 50 consecutive gait cycles from each patient. Kinematic variability of gait was analysed using the uncontrolled manifold technique (UCM). The position of the centre of mass (COM) was chosen as the task variable for the analysis. Results showed that our patient cohort were able to maintain a stable COM whilst walking, through adopting variable combinations of hip, knee and ankle kinematics. The greatest magnitudes of instability (based on the UCM ratios) occurred during initial contact and terminal stance. Active extension of the knee joint to approximately 5° is required during these gait cycle events, meaning that these gait events are highly quadriceps dependent. This study identified and quantified components of the gait cycle where patients with knee OA are most unstable. Employment of this technique could therefore allow specific personalised prescription for prehabilitation and rehabilitation.

1. Introduction

Approximately 23% of people over the age of 60 suffer from knee osteoarthritis (OA) [1]. Knee OA is a degenerative joint disease which causes pain, reduced muscular strength and limited function to the affected joint [2,3]. Consequently, patients suffering from late- to end-stage OA become limited in their mobility [1].

Koyama and colleagues stated recently that increased stiffness of the joint coupled with reduced muscular strength alters the motor control mechanism, ultimately compromising stability [4]. Stability can be quantified in terms of gait variability [5–7]. Although having a variable gait is natural, the extent of variability and the patterns observed in variability have been found to differ in those suffering from OA [5,8,9]. This could affect their ability to react to perturbations, potentially increasing the risk of falling and limiting the extent and speed of activity the patient feels safe to undertake [7,10,11].

Given the complexity of gait, there are limited ways in which researchers and clinicians can objectively assess its overall variability from cycle-to-cycle [7,12,13]. Recent studies have used a method known as the uncontrolled manifold (UCM) hypothesis to investigate

the relationship between motor control and variability in gait [14–16]. The populations in the studies by Papi et al. [14] and Black et al. [15] were stroke survivors and pre-adolescents with and without Down syndrome, respectively.

In these studies, the UCM method quantified the combinations of elemental variables (joint degrees of freedom) that successfully stabilised the centre of mass (COM): ‘good variability’, and those which compromised the stability of the COM: ‘bad variability’ [14,15]. Here, stabilisation of the COM refers to the ability of the elemental variables to maintain a consistent mean COM position over numerous trials, despite showing inter-trial variability. Combinations of elemental variables that lead to a deviation of the COM away from its mean position compromise COM stability. Kinematic synergy was found to exist in each population in these studies, meaning that the ‘good variability’ (variance within the UCM) outweighed the ‘bad variability’ (variance orthogonal to the UCM) [14,15]. However, variability was increased compared to normal, implying that the central nervous system had employed a more variable gait in order to maintain a stable COM during walking. This strategy is believed to reduce COM instability, but to leave the subject more vulnerable to external or internal

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therefore prevent the COM from moving too far laterally. It could also be a pain-avoidance mechanism, adopted by those with predominantly medial knee OA, as was the case in this sample, where 70% had a varus knee deformity. Although this study identified patients with valgus and varus knee deformities, the differences in gait variability between both groups were not investigated due to the small size of the valgus group. Future work will expand on this study to address this limitation.

Despite the fact that frontal plane ratios were relatively consistent throughout the gait cycle (Fig. 3), slightly higher ratios were detected during mid-stance and initial swing phases, suggesting that a higher degree of variance was beneficial in stabilising the COM mediolaterally.

In general, more kinematic variability was exhibited in the sagittal plane than frontal the plane, suggesting that a higher degree of variability was employed during gait to maintain a stable COM in this plane in our population. Some of this kinematic variability may be explained by the freedom of the patients to alter their walking speed during trials. However, given that walking speed naturally fluctuates, we are confident that the data presented here is a better representation of gait variability than if we had imposed a fixed walking speed on the patients.

Given the novelty of this study, our data cannot be compared directly to previously published literature. However, our study did show similarities to others that applied the UCM method to gait data [14,15]. As in our study, Papi et al. and Black et al. showed that kinematic synergy existed in stroke survivors and pre-adolescents with Down syndrome, suggesting that people with pathological gait were able to maintain a stable COM through employing variable gait kinematics [14,15]. Stroke survivors were on average shown to have higher sagittal plane ratios during stance than knee OA patients, but OA patients had greater stability at foot strike [14]. Pre-adolescents with Down syndrome had similar ratios during foot strike to knee OA patients [15]. When compared to healthy older adults, knee OA patients were found to have lower sagittal plane ratios during the stance phase of gait [14].

When devising our experimental protocol, we were aware of the differences that arise in some biomechanical parameters between over-ground and treadmill gait. We did not believe it appropriate to record over-ground walking in this study as tens to hundreds of consecutive cycles must be recorded to report gait variability. Hence, a large amount of space and additional motion capture equipment would have been required to record 50 consecutive cycles. To optimise our treadmill protocol, a long (2m) treadmill was used. This was deemed suitable as short treadmill lengths have been ascribed to some of the differences in biomechanical parameters of treadmill gait [26–28]. We are therefore confident that the methodology used in this study represented gait variability in elderly OA individuals to the best ability.

One way in which our methodology could be improved in future is by calculating each body segment COM with respect to its mass then summing the results for a better representation of the COM.

5. Conclusion

A variable gait is employed to stabilise the centre of mass in patients with OA of the knee. Kinematic synergy was confirmed in this population. Weakness of the quadriceps is thought to decrease sagittal plane stability in this patient cohort. This technique may allow specific personalised prescription for prehabilitation and rehabilitation of knee OA patients.

Conflict of interest

None.

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References

- [1] B. Heidari, Knee osteoarthritis prevalence, risk factors, pathogenesis and features: part I, *Caspian J. Intern. Med.* 2 (2011) 205–212.
- [2] R. Shenoy, P.S. Pastides, D. Nathwani, (iii) Biomechanics of the knee and TKR, *Orthop. Trauma* 27 (6) (2013) 364–371.
- [3] M. Urwin, D. Symmons, T. Allison, T. Brammah, H. Busby, M. Roxby, A. Simmons, G. Williams, Estimating the burden of musculoskeletal disorders in the community: the comparative prevalence of symptoms at different anatomical sites, and the relation to social deprivation, *Ann. Rheum. Dis.* 57 (11) (1998) 649–655.
- [4] Y. Koyama, H. Tateuchi, R. Nishimura, X. Ji, H. Umegaki, M. Kobayashi, N. Ichihashi, Relationships between performance and kinematic/kinetic variables of stair descent in patients with medial knee osteoarthritis: an evaluation of dynamic stability using an extrapolated center of mass, *Clin. Biomech.* 30 (10) (2015) 1066–1070.
- [5] T. Alkjaer, P.C. Raffalt, H. Dalsgaard, E.B. Simonsen, N.C. Petersen, H. Biddal, M. Henriksen, Gait variability and motor control in people with knee osteoarthritis, *Gait Posture* 42 (4) (2015) 479–484.
- [6] T. Herman, N. Giladi, T. Gurevich, J. Hausdorff, Gait instability and fractal dynamics of older adults with a cautious gait: why do certain older adults walk fearfully? *Gait Posture* 21 (2) (2005) 178–185.
- [7] A. Mahmoudian, S. Bruijn, H.R.F. Yakhani, O.G. Meijer, S.M.P. Verschueren, J.H. van Dieën, Phase-dependent changes in local dynamic stability during walking in elderly with and without knee osteoarthritis, *J. Biomech.* 49 (1) (2015) 80–86.
- [8] N.A. Bernstein, *The Co-ordination and Regulation of Movements*, Pergamon Press, Oxford, 1967.
- [9] R.M. Kiss, Effect of severity of knee osteoarthritis on the variability of gait parameters, *J. Electromyogr. Kinesiol.* 21 (2011) 695–703.
- [10] X. Lin, O.G. Meijer, J. Lin, W. Wu, X. Lin, B. Liang, J.H. van Dieën, S.M. Bruijn, Frontal plane kinematics in walking with moderate hip osteoarthritis: stability and fall risk, *Clin. Biomech.* 30 (8) (2015) 874–880.
- [11] B.E. Maki, Gait changes in older adults: predictors of falls or indicators of fear, *J. Am. Geriatr. Soc.* 45 (3) (1997) 313–320.
- [12] J.M. Hausdorff, D.A. Rios, H.K. Edelberg, Gait variability and fall risk in community-living older adults: a 1-year prospective study, *Arch. Phys. Med. Rehab.* 82 (8) (2001) 1050–1056.
- [13] F. Riva, M. Bisi, R. Stagni, Gait variability and stability measures: minimum number of strides and within-session reliability, *Comp. Biol. Med.* 50 (2011) 9–13.
- [14] E. Papi, P.J. Rowe, V.M. Pomeroy, Analysis of gait within the uncontrolled manifold hypothesis: stabilisation of the centre of mass during gait, *J. Biomech.* 48 (2) (2015) 324–331.
- [15] D.P. Black, B.A. Smith, J. Wu, B.D. Ulrich, Uncontrolled manifold analysis of segmental angle variability during walking: preadolescents with and without Down syndrome, *Exp. Brain Res.* 183 (2007) 511–521.
- [16] X. Qu, Uncontrolled manifold analysis of gait variability: effects of load carriage and fatigue, *Gait Posture* 36 (2) (2012) 325–329.
- [17] M.L. Latash, J.P. Scholz, G. Schöner, Towards a new theory of motor synergies, *Motor Control* 11 (3) (2007) 276–308.
- [18] J.G.A. Cashback, H.R. McGregor, P.L. Gribble, The human motor system alters its reaching movement plan for task irrelevant, positional forces, *J. Neurophysiol.* 113 (2015) 2137–2149.
- [19] E.S. Groot, W. Suintay, A joint coordinate system for the clinical description of three-dimensional motions: application to the knee, *Trans. Am. Soc. Mech. Eng.* 105 (1983) 136–144.
- [20] G. Wu, P.R. Cavanagh, ISB recommendations in the reporting for standardization of kinematic data, *J. Biomech.* 28 (10) (1995) 1257–1261.
- [21] A. Cappozzo, F. Catani, U. Della Croce, A. Leardini, Position and orientation in space of bones during movement: anatomical frame definition and determination, *Clin. Biomech.* 10 (4) (1995) 171–178.
- [22] G.F. Tawy, P.J. Rowe, Is the instrumented pointer method of calibrating anatomical landmarks in 3D motion analysis reliable, *J. Biomech.* 53 (2017) 205–209.
- [23] J.G. Remelius, J. Hamill, R.E.A. van Emmerik, Prospective dynamic balance control during the swing phase of walking: stability boundaries and time-to-contact analysis, *Hum. Mov. Sci.* 36 (2014) 227–245.
- [24] J. Perry, J.M. Burnfield, *Gait Analysis. Normal and Pathological Function*, 2nd ed., SLACK Incorporated, NJ, USA, 2010.
- [25] A.M. Murray, A.C. Thomas, C.W. Armstrong, B.G. Piterosimone, M.A. Tevald, The associations between quadriceps muscle strength, power, and knee joint mechanics in knee osteoarthritis: a cross-sectional study, *Clin. Biomech.* 30 (10) (2015) 1140–1145.
- [26] F. Alton, L. Baldey, S. Caplan, M.C. Morrissey, A kinematic comparison of over-ground and treadmill walking, *Clin. Biomech.* 13 (6) (1998) 434–440.
- [27] L.H. Sloop, M.M. van der Krogt, J. Harlaar, Self-paced versus fixed speed treadmill walking, *Gait Posture* 39 (1) (2014) 478–484.
- [28] G.M. Strathy, E.Y. Chao, R.K. Laughman, Changes in knee function associated with treadmill ambulation, *J. Biomech.* 16 (7) (1983) 517–522.