The Journal of Frailty & Aging 14 (2025) 100103

Contents lists available at ScienceDirect

The Journal of Frailty & Aging

journal homepage: www.elsevier.com/locate/tjfa

Review

Walking through aging: A review of gait laboratory-based assessments and geriatric syndromes

Catherine van't Hoff [a,*], Anthony Bull [b], Michael Fertleman [a]

[a] Cutrale Perioperative and Ageing Group, Department of Bioengineering, Imperial College London, United Kingdom
[b] Department of Bioengineering, Imperial College London, United Kingdom

ARTICLE INFO

Keywords:
Gait
Transfer activities
Aging

ABSTRACT

Gait is a complex, multifaceted process involving multiple organ systems. Both gait and transfer activities are key requirements for independent living. As individuals age, gait undergoes characteristic changes, including reduced walking speed, altered stride length, and increased variability. These changes are closely linked to the frailty syndromes of immobility, instability, cognitive impairment, incontinence, and iatrogenic harm.

Alterations in gait and transfer activities can serve as early predictors of falls, increased dependency, cognitive decline, and depression. Urinary incontinence and nocturia are associated with reduced mobility, a higher risk of falls, and fractures. Notably, the urge to void itself can influence gait patterns. Medications, particularly anticholinergics and polypharmacy, further contribute to gait disturbances, compounding falls risk.

Given its strong association with cognitive and functional decline, gait analysis is a crucial component of comprehensive geriatric evaluation. Recognising and addressing gait abnormalities can enhance patient outcomes by mitigating the broader impact on geriatric frailty syndromes.

1. Introduction

Gait and transfer activities (such as the ability to stand from a chair) are key requirements for independent living [1]. They require energy, strength, movement control and communication between multiple organ systems including the musculoskeletal, cognitive, and cardiorespiratory systems [2–4]. The increasing prevalence of musculoskeletal conditions (affecting 53 % of over 65 year olds globally), reflects our aging population [5]. Transfer activities such as sit-to-stand can use up to 97 % of available strength in an older patient [5] and those unable to perform sit to stand are at increased risk of injury and prolonged hospital admission [5]. Gait impairments in older people are common, affecting 72 % of adults aged over 80 years [6].

Gait changes with age but slowing gait is not necessarily an inevitable consequence of aging [2]. It may reflect damaged organ systems (from increased prevalence and severity of age-associated diseases) [7] or the inability to meet the required energy costs [2]. Analysis of gait and transfer activities provides useful information to improve diagnosis and outcome prediction in a wide spectrum of diseases including Parkinson's disease and stroke [8] as well as guiding assessment of treatment efficacy and rehabilitation across frailty syndromes [9]. In fact, changes in gait variables can be observed before the appearance of clinically functional disability [10] and recognising early changes in gait allows clinicians to potentially intervene or optimise patients to help improve outcomes. This review examines use of gait analysis in relation to geriatric syndromes and how gait can be a clinically meaningful biomarker in aging populations.

1.1. Methods of quantifying gait and transfer activities

Gait analysis focuses on spatiotemporal variables (measures of time or space), kinematic variables (measures of joint angles and range of movement) and kinetic variables (measures of force or momentum) [11]. The gold standard for measuring and analysing gait and transfer activities is three-dimensional optical motion tracking [8] described as the gait laboratory. Gait laboratories have several components (outlined in Table 1), and can vary between institutions; however, most centre on 2-D or 3-D motion capture with the addition of force plates, accelerometers or instrumented treadmills [12]. Fig. 1 shows a typical gait laboratory within a university research setting.

A gait laboratory provides accurate, precise and reliable gait data and is particularly useful in research [8,10]. It examines objective

---

* Corresponding author.
E-mail address: catherine.vant-hoff24@imperial.ac.uk (C. van't Hoff).

https://doi.org/10.1016/j.tjfa.2025.100103
Received 9 July 2025; Received in revised form 19 September 2025; Accepted 2 October 2025

measures which are not otherwise captured using more traditional methods of questionnaires and scoring systems relying on subjective patient report [10]. 3D gait analysis is safe and non-threatening, even in severe gait dysfunction [10].

In 1988, *Klenerman et al.* recognised the usefulness of the gait laboratory and its tendency to exclude older adults. They called for the use of the gait laboratory to move out of the sphere of research and into clinical practise by suggesting simple measures to assess gait in a clinical context [13]. There are numerous tools that have been suggested to simplify gait analysis in clinical practice, such as the timed-up-and-go test or the short physical performance battery. Although such methods are simple, accessible and low cost, observational gait analysis is limited by observer background and experience, resulting in high inter-user variability leading to low validity, specificity and reliability, and so they may not be adequate for analysing the multifaceted aspects of gait variability and complexity [8].

Therefore, the need for detailed analysis in the gait laboratory persists, and understanding of how gait interacts with geriatric syndromes continues to develop. The remainder of this article explores how gait analysis can be linked to geriatric syndromes, as described by Isaacs in 1965 [14], and its relevance for 21st century geriatricians and professionals performing a comprehensive geriatric assessment.

1.2. Gait laboratory measures and geriatric syndromes

Gait and transfer activities change with age, reflecting damaged organ systems [7] or an inability to meet required energy costs [2]. Detailed analysis of gait and transfer activities provides evidence for the changes typically seen in aging; for example, older adults walk more slowly, have a shorter step and stride length, wider step, and higher gait variability [3].

Falls and immobility

Falls are a major public health issue, with high personal and societal cost [15]. Moreover, they reduce quality of life and increase morbidity and mortality [16,17]. A third of adults aged over 65 will fall each year [16,18,19]. Risk factors for falls can be categorised as extrinsic (environmental hazards) or intrinsic (reduced muscle strength or impaired proprioception) [15]. Patients who are unable to compensate for intrinsic factors may have altered gait and therefore gait can be seen as a surrogate for falling [15].

Multiple aspects of gait are associated with falls [15], reflecting the complex and multifactorial nature of gait and the constraints of analysing gait within clinical research [15]. No specific aspect of gait has been associated with single falls, although participants who experience multiple falls show greater variability in step length and greater variability of time in the double-support phase [15] (which is when both feet are on the ground). There is also a non-linear relationship between gait speed, cadence and step-time variability in frequent fallers [15].

Activities of daily living are complex motor tasks that require an interplay between biomechanics, physiology, trajectory planning and motor control [20]. Compensation is the alteration in movement strategy compared to that of baseline or of a control to prevent movement limitations [20]. There are two main methods of compensation: changes in movement trajectory (moving an alternative limb) or changes in muscle recruitment (co-contraction of alternative muscles without a change in trajectory) [20]. Despite the neuromuscular system declining from the age of 20 years, many studies do not allow the use of compensation when analysing gait in an experimental context [18].

Energy related costs may be the primary driver for standard movements such as gait [20]. However, particularly in older adults, emphasis may be placed on alternative objectives such as stability or pain avoidance [20]. Adults follow stereotypical movement patterns, conducted through the basal ganglia (based on choice, motivation and context), adapted through sensory input, and reinforced through external rewards or the perception of success, resulting in the reinforcement of these stereotypical movement patterns [18]. Similarly, methods of compensation can also follow stereotypical patterns, for example older men consistently using an arm push-off when moving from seated to standing [18].

The inability to stand independently from a chair is associated with increased risk of falling, risk of fracture and institutionalisation [1]. Large joint torques are required in addition to accurate balance control, and lower extremity strength (for example in the knee or ankle) is a significant predictor of the lowest height of a successful chair rise [1]. However, chair rise patterns change with aging, with older adults using more hip muscle strength and a more upright trunk position at lift-off compared to younger adults [1]. Additionally, to stand more quickly, older adults generate more horizontal momentum whilst in contact with the chair to improve stability [1].

Participants using armrests as a method of compensation are significantly older, have a slower timed-up-and-go time, and have a reduced range of movement in both ankle and hip flexion [18]. Previously, the use of compensation has been attributed to muscle weakness, however, while older men consistently used pushing-off with arms, they were not weaker than young women (who did not compensate) [18]. The authors attribute this to be related to the participants' perception of stability and therefore perceived need to compensate [18], or impaired ability to regain balance in the event of a trip or stumble. It is suggested that individuals may aim to compensate prior to failure given environmental and physical uncertainties to prevent risks of falls (and their consequences) [18].

Table 1
Components of a typical gait laboratory.

Instrument	Method	Output	Advantages	Disadvantages
Cameras	Measure movement of trackers fixed to surface of participants.	Examination for spatiotemporal variables (walking speed, stride length or cadence (steps per minute)) and kinematic variables (joint angle and range of motion, speed, extent and direction of movement of body segments or joints) [12].	High performance. Accurate data. Complex trials of motion across multiple planes. Gold standard for instrumented gait analysis. Non-invasive.	Non-portable. High cost. Set-up, calibration and training required. Risk of soft-tissue artefact. Indoor only.
Force plates	Measure how a participant interacts with the environment such as the floor, chair or bed.	Kinetic variables (movement forces, joint movement, power and ground reaction force) [12].	High performance. Accurate data. Gold standard for instrumented gait analysis. Non-invasive.	Limited portability. High cost and specialist set-up required.
Bespoke instruments such as electromyography (EMG)	Specialised uses such as quantifying muscle activation.	Measurement of EMG allows assessment of muscular effort.	Allows synchronisation with other physiological measurements. Non-invasive.	May require specialist algorithms for data processing. Lack of normative activation patterns.

Another method of compensation is protective stepping [17]; older adults are least likely to tolerate lateral waist-pulls due to diminished lateral balance following reduced use of hip abductor muscles [17]. This was most clearly demonstrated in older adults who have fallen previously, but was also present in older, non-fallers [17].

Gait velocity remains stable until the age of 60 years and then declines by 1 % per year until the age of 70 years when the rate of decline increases to 15 % per decade [7]. There is an established link between gait speed and survival [2,21]. Slower gait speeds correlate with increased mortality in older adults [22,23], evidenced by increased falls, cognitive impairment, and functional decline [21,23]. Frailty models, such as Fried's frailty phenotype and other routine clinical assessments including the timed-up-and-go and short physical performance battery include assessment of gait speed. It is a quick, easily accessible and cheap test available to all clinicians at the bedside or in outpatient clinics. Early identification of patients with frailty or impaired gait speed allows for intervention in the form of comprehensive geriatric assessment, to potentially mitigate the effects of frailty.

The gait speed at which healthy aging crosses over to poor health and function is debated but 0.6 to 0.8m/s are the speeds most frequently cited [2], with a gait speed of $<$1.0m/s cited as a strong predictor of falls in older people [23]. However, the UK uses a minimum walking speed of 1.2m/s (double the minimum threshold previously found) to traverse a pedestrian crossing safely [24], reflecting the issues older adults may have in accessibility and equality.

Cognitive impairment

In addition to the musculoskeletal system, effective gait requires cognition and executive control [3]. Cognitive decline often presents with impaired working memory and executive function. In gait analysis this is reflected by reduced attention, postural control and processing speeds [3]. Specifically, impaired pace predicted decline in executive function, and disturbances in rhythm were associated with impaired episodic memory [25]. Cognitive function is also related to gait speed, step time, step length and gait variability [21]. Motor impairments can precede cognitive impairments [25], and gait impairments can predict both earlier cognitive decline when compared to conventional cognitive testing and the risk of progression of cognitive impairment [3,21].

Older adults with depression typically experience psychomotor slowing, manifesting as lack of initiation, dysfunction in executive function, and deficits in attention or concentration [21]. In patients with mild cognitive impairment, there is a significant association between slower gait speed with depression symptoms (when adjusting for confounding variables) resulting in a two-fold increase in the rate of depression when compared to normal gait speed [21]. Depression may be a reversible contributor to cognitive impairment and early identification of patients with slow gait speed and mild cognitive impairment may allow for more timely interventions to reduce the risk of progression to dementia [21]. Additionally, slower gait speed can be used as a predictor of a new diagnosis of depression in later life [21].

Dual task conditions (walking and talking, avoiding obstacles or making turns) becomes more challenging in advanced age resulting in a more unstable and slower gait, and poor performance can predict risk of future falls [3]. Dual task analysis increases the sensitivity to gait analysis, however, the exact mechanism of reduction in gait performance is unknown. A suggested cause attributes reduced attention resources which directly correlates with grey matter volume in the frontal cortical region of patients with mild cognitive impairment [3].

Knee kinematic analysis significantly differs in patients with mild cognitive impairment compared to those with normal cognition, particularly under dual task conditions [3]. Patients with mild cognitive impairment had a larger knee extension angle closer to 0 during the standing phase and this reflected worse knee control and increased instability [3]. This contrasts with older adults with normal cognition who often favour a hyperextended knee position; possibly to give assistance in weight transfer or to increase joint stability [3]. Thus, compensatory strategies normally used may be lost in cognitive impairment and so explain the increased risks of falls with reducing cognition.

Incontinence

Urinary incontinence, particularly urge or mixed incontinence, is linked with reduced functional ability, reduced mobility, falls and fractures [26,27]. Nocturia is also associated with increased risk of falls [28]. Overactive bladder is associated with both falls and gait speed [28], with slower gait speeds associated with more severe symptoms [26,27] . However, bladder symptoms were not affected by other markers of sarcopenia such as muscle mass or grip strength [26]. In a cohort of continent women, gait velocity and stride length were significantly reduced when participants had a strong desire to void (compared

Fig. 1. Typical gait laboratory showing 4 motion capture cameras, 2 ground force plates and an instrumented chair.

to their first desire to void or their post-void gait) [28].

There are several theories linking gait and incontinence, both requiring complex neurological and sensorimotor processes [26,28]. These include: the increased time required for patients with impaired mobility to get to the toilet resulting in incontinence, reduced travel and mobility to maintain proximity to bathroom facilities further exacerbating deconditioning, or a common risk factor such as cognitive impairment [27]. It has further been suggested that a strong desire to void results in a dual task situation and controlling continence is prioritised over maintaining a normal gait [28]. Finally, a mechanical theory of increased intra-abdominal pressure (secondary to bladder filling and co-contraction of the pelvic floor) results in changes in trunk and abdominal muscle activity; this results in reduced ability to correct for posture (and therefore impaired balance) and a change in the centre of mass (resulting in reduced stability) [28].

Iatrogenic and polypharmacy

Polypharmacy increases the risk of falls by 5 times and is associated with lower gait speed and higher gait variability [4]; participants taking a higher number of medications have poorer gait performance compared to those taking fewer medications [4]. Disturbances in gait are reported more frequently by people taking 4 or more prescribed medications [7]. Patients taking 3 or fewer medications have increased stride length and reduced double support time compared to those taking 4 or more medications [7]. When adjusting for age, sex and co-morbidities, there is a dose dependent relationship between gait and polypharmacy, with the addition of each new medication increasing the risk of gait decline by 12 % and the risk of new falls by 5 % [4].

In addition to the number of medications, certain classes of medications (such as anticholinergics, psychoactive medications and diuretics) are also known to affect gait. One Swedish case-control series examining 20 of the most prescribed medications in older adults, showed that most medications (apart from cardiovascular medications and oestrogens) had a positive association with falls [29]. However, there may be confounders as medications such as B12 and folic acid given for anaemia, treat potential symptoms of dizziness and therefore reducing falls risk [29].

Anticholinergics have side effects that include poor mobility, falls, functional decline and psychomotor slowing in older adults [30]. In a recent meta-analysis, 15 out of 16 studies showed increased anticholinergic burden was significantly associated with impaired mobility (evidenced by worsened hand-grip strength, timed-up-and-go times, impairments in activities of daily living or worsened short physical performance battery scores) [31]. The use of any anticholinergic drug was significantly associated with falls, poorer dynamic balance and impaired gait speed, even when adjusting for confounders including cognitive impairment [30], as well as being associated with being unable to stand from a chair independently, worse balance and poor extremity function [32].

Psychoactive medications (such as benzodiazepines and antidepressants) have been independently associated with increased risk of falls and increased gait instability in older adults [33]. Furthermore, the use of psychoactive medications was associated with greater variation in stride time compared to control participants [33]. Psychoactive medications have also been associated with reduced gait speed in older adults [34]. However, it is worth noting that, depression may also contribute to gait impairments and so the variability in stride time may be more an indirect marker of psychiatric symptoms than medications themselves.

In a cohort of community-dwelling older adults, diuretics are associated with significantly reduced gait speed and increased falls risk [34]. Possible mechanisms linking diuretics and falls risk relate to hypovolaemia and postural symptoms or electrolyte abnormalities reducing alertness [34]. Statins are associated with increased stride time variability [34] and reduced gait speed [35]. However, the use of concomitant ACE inhibitors or beta-blockers reduces this disparity [35]. The clinical relevance and mechanism for the effect of statins on gait speed is currently uncertain [34].

Gait analysis can also be used following iatrogenic intervention. Despite successful total hip arthroplasty (with self-reported improvement in pain and function), aberrant preoperative gait patterns may persist postoperatively [12,36], resulting in 14–22 % of patients reporting limitations in function or lack of clinically meaningful recovery [37]. Compared to controls, postoperative total hip arthroplasty patients walk more slowly, with reduced range of motion with reduced stride length and reduced hip range of motion even 12 months postoperatively [12]. This is particularly relevant because aberrant postoperative gait can increase the risk of undergoing contralateral joint arthroplasties [38–40].

Bahl et al. (2018) conducted a meta-analysis of changes in gait following total hip arthroplasty for osteoarthritis [12]. Spatiotemporally, patients demonstrated a moderate deficit in walking speed 6 weeks postoperatively that persisted but reduced in magnitude at 3 and 12 months compared to controls [12]. Stride length also had large deficits at 6 weeks reducing in magnitude at 3 and 6 months but were also still persistent at 12 months [12]. Kinematically there was a reduction in range of movement in the sagittal and coronal planes of the hip compared to controls at 6 weeks with decreasing magnitude at 3 and 6 months [12]. Kinetically a small number of studies demonstrated that peak hip abduction was comparable to controls at 3 months [12].

Hospitalisation itself can also cause iatrogenic harm. It accentuates muscle disuse and changes in muscle composition, with a short hospital admission causing a percentage loss of 3–4 % of muscle mass [41]. The hospital environment may result in reduced food and fluid intake, reduced physical activity (older adults spend over 80 % of their hospital admission in bed), physical and mental stress and sometimes surgical procedures, all of which are not reflected in the research environment [41]. Muscle disuse through limb immobilisation (in both young and old patients) results in a loss of 2–6 % of muscle mass and 8–22 % loss of muscle strength [41].

However, there remains no consensus as to what constitutes an "acceptable" or "good" outcome regarding gait patterns following total hip arthroplasty [37]. Subjective assessments only weakly correlate to gait parameters (suggesting self-perceived physical status did not match objective physical performance) [10]. Therefore, analysis of postoperative outcomes in the gait laboratory alone is unlikely to be sufficient.

In summary, gait and transfer activities are both essential for independent living. However, they are altered in an often stereotypical manner in advancing age, leading to changes in gait speed, gait variability, stride length and width, changes in centre of gravity and joint power and range of movement. Compensation may be used to maintain successful movement, and also often follows stereotypical patterns. These changes both reflect and contribute to geriatric frailty syndromes, as illustrated in Fig. 2.

1.3. *Future developments*

The gait laboratory provides high quality and accurate data which can be clinically exploited [8]. There is a downside, but this centres inevitably around costs and logistics and the fact that they are often limited to research facilities [8]. Furthermore, output can be complex and multidimensional and is sometimes affected by a lack of standardisation [8,10,42].

There has been a major increase in the use of 3D gait analysis in the past decade with technological advancements in collecting data [10]. Future developments include a move towards wearable sensing devices. This is a rapidly transforming area and includes technology such as magnetometers (to assess joint angles), tri-axial accelerometers (to assess risk of falls), and force sensors within shoe insoles (to assess gait symmetry) [8]. A summary of newer technologies is outlined below in Table 2, some of which have been validated for neurological conditions such as Parkinson's disease, stroke or Huntington's disease [11].

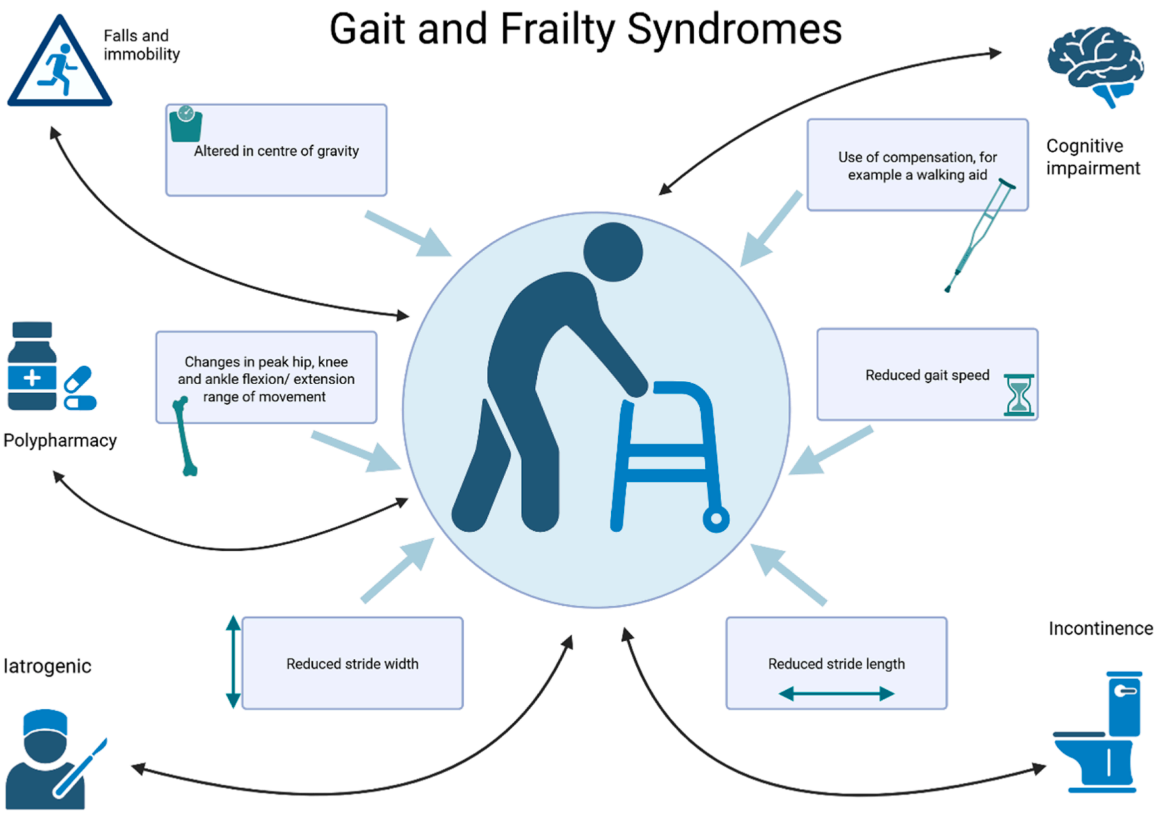

Fig. 2. an illustration of the changes in gait seen in aging. Created in BioRender. van't Hoff, C. (2025) https://BioRender.com/inik3fg.

Table 2
A summary to newer technologies to assess gait.

Technology	Gait parameters assessed	Advantages	Disadvantages
Magnetometers	Joint angles, kinematic and spatiotemporal variables, orientation, posture	Portable.	Discrepancies in sensor positioning, reducing accuracy.
Tri-axial accelerometers	Stability Risk of falls	Easy to implement into clinical practice.	Risk of error relating to sensor positioning.
Force sensors, eg shoe insoles	Centre of pressure trajectories, pressure monitoring, ground reaction forces	Cost-effective. Portable.	Needs subject-specific calibration. Risk of drift or distortion from prolonged/ repeated use. Low accuracy compared to force plates.

"Marker-less tracking" using cameras can be used to measure spatiotemporal variables but they are less accurate. They are often cheap and can sometimes be used outside the laboratory such as in outpatients clinic. Inertial measurement units are larger trackers affixed to the body that don't require cameras. They include technology like that in a smartphone, measuring spatiotemporal variables with a low level of accuracy such as step counts. Force plates can also be taken out of the laboratory and used in technologies such as pressure matts or insoles, allowing measurement of variables related to force. This allows capture of real-world data, resulting in the mobile gait laboratory becoming a reality. The use of artificial intelligence allows the assessment of high volumes of data produced from multimodality sensors and various physiological signals to provide information of underlying health conditions [8].

New technology has the advantages of potentially lower cost, low set-up time, reduced complexity, and allowing for continuous monitoring that is not limited to a walkway within the laboratory [8]. It is likely to be an ongoing area of development as technology advances. However, there is currently limited research into the efficacy, reliability, and validity of its use in the clinical setting [8]. There is a lack of standardisation and inconsistencies regarding data interpretation resulting in limited evidence for their usage [11]. Furthermore, there are important ethical considerations regarding remote data collection, monitoring and data storage, particularly by that of private companies.

2. Conclusion

Gait impairments affect 35 % of adults aged over 70 years and 72 % of adults aged over 80 years [6]. Performance in gait and transfer activities serves as a predictor of survival, cognitive decline, falls, and quality of life [6]. Therefore, analysis of gait can be used as a key clinical tool, particularly in geriatric medicine. Simple measures such as measuring gait speed are reflective markers of gait and easily accessible in clinical practice. However, the use of gait laboratory remains the gold standard for analysing gait and should be an area of further development. This article has demonstrated how gait affects all geriatric syndromes from falls, immobility, incontinence or iatrogenic harm. Early identification of gait impairments may allow for more timely clinical intervention, for example in the context of cognitive impairment or depression when gait impairments are a more sensitive marker than early cognitive testing.

Regrettably, the use of the gait laboratory in routine clinical practise remains limited, due to barriers such as specialist equipment, expertise and cost. In 2023, the Chief Medical Officer's Report highlighted a paucity of research focussing on older adults with multimorbidity and called for the removal of barriers for such people being involved in clinical trials [43]. Furthermore, musculoskeletal conditions were named as one of the top four research priorities in older adults [43]. However, currently NICE (National Institute for Health and Care Excellence) only recommend the use of one sensor-based digital technology assessment, to assess adults with falls or osteoarthritis [44]. Since gait affects all aspects of geriatric syndromes, its assessment must remain a core component of bedside clinical evaluation and a focussed area of development in geriatric research. Furthermore, with ongoing technological advancements, the incorporation of objective gait analysis into routine clinical practise is likely to become feasible and increasingly essential.

Ethical approval

Ethical approval was not required.

Funding

No specific grant from any funding agency in the public, commercial or not for profit sectors.

CRediT authorship contribution statement

Catherine van't Hoff: Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation, Conceptualization. **Anthony Bull:** Writing – review & editing, Supervision. **Michael Fertleman:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

n/a.

References

[1] Gross MM, Stevenson PJ, Charette SL, Pyka G, Marcus R. Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. Gait Posture 1998;8:175–85.

[2] Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al. Gait speed and survival in older adults. JAMA 2011;305(1). https://doi.org/10.1001/jama.2010.1923.

[3] Ali N, Liu J, Tian H, Pan W, Tang Y, Zhong Q, et al. A novel dual-task paradigm with story recall shows significant differences in the gait kinematics in older adults with cognitive impairment: a cross-sectional study. Front Aging Neurosci 2022;14. https://doi.org/10.3389/fnagi.2022.992873.

[4] Montero-Odasso M, Sarquis-Adamson Y, Song HY, Bray NW, Pieruccini-Faria F, Speechley M. Polypharmacy, gait performance, and falls in community-dwelling older adults. Results from the gait and brain study. J Am Geriatr Soc 2019.

[5] Smith SHL, Reilly P, Bull AMJ. A musculoskeletal modelling approach to explain sit-to-stand difficulties in older people due to changes in muscle recruitment and movement strategies. J Biomech 2020;98. https://doi.org/10.1016/j.jbiomech.2019.109451.

[6] Maity S, Das H, Chakrawarty A, Devanbu VGC. Gait analysis and geriatric syndromes: an association among elderly patients attending a teaching hospital of Delhi. J Fam Med Prim Care 2024;13(6):2329. https://doi.org/10.4103/jfmpc.jfmpc_1728_23.

[7] Gabaldon J, Wood RH, Murphy E, Keeley DW. Medication status and gait mechanics in older adults: a multivariate analysis. J Geriatr Phys Ther 2020;43(2):55. https://doi.org/10.1519/jpt.0000000000000253.

[8] Hulleck AA, Menoth Mohan D, Abdallah N, El Rich M, Khalaf K. Present and future of gait assessment in clinical practice: towards the application of novel trends and technologies. Front Med Technol 2022.

[9] Choi W, Jeong H, Oh S, Jung T-D. Instant gait classification for hip osteoarthritis patients: a non-wearable sensor approach utilizing Pearson correlation, SMAPE, and GMM. Biomed Eng Lett 2025;15(2). https://doi.org/10.1007/s13534-024-00448-2. 301EP–310.

[10] Ornetti P, Maillefert J, Laroche D, Morisset C, Dougados M, Gossec L. Gait analysis as a quantifiable outcome measure in hip or knee osteoarthritis: a systematic review. Jt Bone Spine 2010;77(5):421. https://doi.org/10.1016/j.jbspin.2009.12.009.

[11] Celik Y, Stuart S, Woo WL, Godfrey A. Gait analysis in neurological populations: progression in the use of wearables. Elsevier BV; 2021.

[12] Bahl JS, Nelson MJ, Taylor M, Solomon LB, Arnold JB, Thewlis D. Biomechanical changes and recovery of gait function after total hip arthroplasty for osteoarthritis: a systematic review and meta-analysis. Osteoarthr Cartil 2018;26(7):847. https://doi.org/10.1016/j.joca.2018.02.897.

[13] Klenerman L, Doses RJ, Weller C, Leeman AL, Nicholson PW. Bringing gait analysis out of the laboratory and into the clinic. Age Ageing 1988;17(6):397–400. https://doi.org/10.1093/ageing/17.6.397.

[14] Morley JE. A brief history of geriatrics. J Gerontol 2004;59A(11):1132–52.

[15] Callisaya ML, Blizzard L, Schmidt MD, Martin KL, Mcginley JL, Sanders LM, et al. Gait, gait variability and the risk of multiple incident falls in older people: a population-based study. Age Ageing 2024;40(4):481. https://doi.org/10.1093/ageing/afr055.

[16] Nowossadeck E, Li LZ, Li J, Xu Q, Ou X. The risk of falls among the aging population: a systematic review and meta-analysis. Front Public Health 2022.

[17] Inacio M, Ryan AS, Bair W, Prettyman M, Beamer BA, Rogers MW. Gluteal muscle composition differentiates fallers from non-fallers in community dwelling older adults. BMC Geriatr 2014;14(37).

[18] Van Der Kruk E, Strutton P, Koizia LJ, Fertleman M, Reilly P, Bull AMJ. Why do older adults stand-up differently to young adults?: investigation of compensatory movement strategies in sit-to-walk. npj Aging 2022;8(1). https://doi.org/10.1038/s41514-022-00094-x.

[19] Lugade V, Klausmeier V, Jewett B, Collis D, Chou L. Short-term recovery of balance control after total hip arthroplasty. Clin Orthop Relat Res 2008;466(12). https://doi.org/10.1007/s11999-008-0488-9.

[20] Van Der Kruk E, Silverman AK, Koizia L, Reilly P, Fertleman M, Bull AMJ. Age-related compensation: neuromusculoskeletal capacity, reserve & movement objectives. J Biomech 2021;122. https://doi.org/10.1016/j.jbiomech.2021.110385.

[21] Naharci MI, Katipoglu B, Veizi B, Tasci I. Gait speed is independently associated with depression symptoms in mild cognitive impairment. Aging Neuropsychol Cogn 2021;29(4):637. https://doi.org/10.1080/13825585.2021.1882932.

[22] Ikemoto T, Arai Y. Locomotive syndrome: clinical perspectives. Clin Interv Aging 2018;Volume 13:819. https://doi.org/10.2147/cia.s148683.

[23] Kyrdalen IL, Thingstad P, Sandvik L, Ormstad H. Associations between gait speed and well-known fall risk factors among community-dwelling older adults. Physiother Res Int 2018;24(1). https://doi.org/10.1002/pri.1743.

[24] Asher L, Aresu M, Falaschetti E, Mindell J. Most older pedestrians are unable to cross the road in time: a cross-sectional study. Age Ageing 2012;41(5):690. https://doi.org/10.1093/ageing/afs076.

[25] Verghese J, Wang C, Lipton RB, Holtzer R, Xue X. Quantitative gait dysfunction and risk of cognitive decline and dementia. BMJ 2007.

[26] Omae K, Yamamoto Y, Kurita N, Takeshima T, Naganuma T, Takahashi S, et al. Gait speed and overactive bladder in the healthy community-dwelling super elderly: the Sukagawa Study. Neurourol, Urodyn 2019;38(8):2324. https://doi.org/10.1002/nau.24148.

[27] Fritel X, Lachal L, Cassou B, Fauconnier A, Dargent-Molina P. Mobility impairment is associated with urge but not stress urinary incontinence in community-dwelling older women: results from the Ossébo study. BJOG: Int J Obstet Gynaecol 2013;120(12). https://doi.org/10.1111/1471-0528.12316.

[28] Booth J, Paul L, Rafferty D, Macinnes C. The relationship between urinary bladder control and gait in women. Neurourol Urodyn 2012;32(1):43. https://doi.org/10.1002/nau.22272.

[29] Kuschel BM, Laflamme L, Moller J. The risk of fall injury in relation to commonly prescribed medications among older people–a swedish case-control study. Oxford University Press (OUP); 2014.

[30] Zia A, Kamaruzzaman S, Myint PK, Tan MP. Anticholinergic burden is associated with recurrent and injurious falls in older individuals. Maturitas 2016;84:32. https://doi.org/10.1016/j.maturitas.2015.10.009.

[31] Phutietsile GO, Fotaki N, Jamieson HA, Nishtala PS. The association between anticholinergic burden and mobility: a systematic review and meta-analyses. BMC geriatrics. Springer Science and Business Media LLC; 2023.

[32] Mehdizadeh D, Hale M, Todd O, Zaman H, Marques I, Petty D, et al. Associations between anticholinergic medication exposure and adverse health outcomes in older people with frailty: a systematic review and meta-analysis. Drugs Real World Outcomes 2021;8(4):431. https://doi.org/10.1007/s40801-021-00256-5.

[33] Poujol L, Annweiler C, Allali G, Fantino B, Beauchet O. EFFECT of Psychoactive Medication on Gait Variability in Community-Dwelling Older Adults: A Cross-Sectional Study. Wiley; 2010.

[34] Osman A, Speechley M, Ali S, Montero-Odasso M. Fall-Risk-Increasing Drugs and Gait Performance in Community-Dwelling Older Adults: Exploratory Results from the Gait and Brain Study. Springer Science and Business Media LLC; 2023.

[35] De Spiegeleer A, Bronselaer A, Mahieu I, Vreys D, Haslbauer A, Leibfarth J, et al. The association between statins and gait speed reserve in older adults: effects of concomitant medication. Springer Science and Business Media LLC; 2025.

[36] Zomar BO, Bryant DM, Hunter SW, Howard JL, Lanting BA. Perioperative gait analysis after total hip arthroplasty: does outpatient surgery compromise patient outcomes? Can J Surg 2021;64(4):E407. https://doi.org/10.1503/cjs.008620.

[37] Foucher KC. Identifying clinically meaningful benchmarks for gait improvement after total hip arthroplasty. J Orthop Res 2015;34(1):88. https://doi.org/10.1002/jor.22996.

[38] Petis S, Howard J, Lanting B, Jones I, Birmingham T, Vasarhelyi E. Comparing the anterior, posterior and lateral approach: gait analysis in total hip arthroplasty. Can J Surg J Can Chir 2018;61(1):50–7. https://doi.org/10.1503/cjs.003217.

[39] Nankaku M, Tsuboyama T, Kakinoki R, Kawanabe K, Kanzaki H, Mito Y, et al. Gait analysis of patients in early stages after total hip arthroplasty: effect of lateral trunk displacement on walking efficiency. J Orthop Sci 2007;12(6):550–4. https://doi.org/10.1007/s00776-007-1178-2.

[40] Foucher KC, Wimmer MA, Moisio KC, Hildebrand M, Berli MC, Walker MR, et al. Time course and extent of functional recovery during the first postoperative year after minimally invasive total hip arthroplasty with two different surgical approaches–a randomized controlled trial. J Biomech 2011;44(3):372–8. https://doi.org/10.1016/j.jbiomech.2010.10.026.

[41] Kouw IWK, Groen BBL, Smeets JSJ, Kramer IF, van Kranenburg J MX, Nilwik R, et al. One week of hospitalization following elective hip surgery induces substantial muscle atrophy in older patients. J Am Med Dir Assoc 2019;20(1):35–42. https://doi.org/10.1016/j.jamda.2018.06.018.

[42] Mazzoli D, Giannotti E, Longhi M, Prati P, Masiero S, Merlo A. Age explains limited hip extension recovery at one year from total hip arthroplasty. Clin Biomech (Bristol Avon) 2017;48(8611877):35–41. https://doi.org/10.1016/j.clinbiomech.2017.07.003.

[43] Chief Medical Officer's Annual Report 2023 Health in an Ageing Society. 2023. https://www.gov.uk/government/publications/chief-medical-officers-annual-report-2023-health-in-an-ageing-society.

[44] National Institute for Health and Care Excellence. *GaitSmart rehabilitation exercise programme for gait and mobility issues medical technologies guidance.* 2024.