Published in final edited form as:

NeuroRehabilitation. 2017 ; 41(4): 765–774. doi:10.3233/NRE-172154.

Walking on uneven terrain in healthy adults and the implications for people after stroke

Kelly A Hawkins, DPT¹, David J Clark, ScD^{2,3}, Chitralakshmi K Balasubramanian, PT, PhD⁴, and Emily J Fox, DPT, PhD^{1,5}

¹Department of Physical Therapy, University of Florida, Gainesville, FL USA

²Brain Rehabilitation Research Center, North Florida/South Georgia Veterans Health System, Gainesville, FL USA

³Department of Aging and Geriatric Research, University of Florida, Gainesville, FL, USA

⁴Department of Clinical and Applied Movement Sciences, University of North Florida

⁵Brooks Rehabilitation, Jacksonville, FL, USA

Abstract

BACKGROUND—One third of individuals after stroke report an inability to walk in the community. Community mobility requires walking adaptability—the ability to adjust one's stepping pattern to meet environmental demands and task goals. Walking on uneven terrain (e.g. grass, gravel) has unique requirements and is a critical component of walking adaptability that has not been investigated in the post-stroke population.

OBJECTIVE—To summarize current knowledge of biomechanical and neuromuscular modifications during uneven terrain negotiation in healthy individuals and discuss implications of post-stroke impairments.

METHODS—Review of eleven studies, identified through a search of relevant literature on PubMed and CINAHL.

RESULTS—On uneven terrain, healthy adults demonstrate numerous gait modifications including a lowered center of mass, increased muscle co-contraction during stance and exaggerated or increased toe clearance during swing. After stroke, changes in muscle activity and limb coordination will likely result in difficulty or inability performing these modifications that healthy adults use to maintain stability and safety when walking on uneven terrain.

CONCLUSIONS—Studies of biomechanical and neuromuscular control of walking on uneven terrain are needed to quantify mobility limitations in adults post-stroke. Such investigations will contribute to the understanding of mobility impairments after stroke and the design of critically important intervention strategies.

Corresponding author: Emily J Fox; University of Florida; Department of Physical Therapy; Box 100154, UFHSC; Gainesville, FL 32610-0154; 352-273-6117; ejfox@phhp.ufl.edu.
ORCID 0000-0003-0142-3497

Declaration of Interest

No potential conflict of interest was reported by the authors.

Keywords

walking adaptability; uneven terrain; stroke; community ambulation; rehabilitation

1. Introduction

Walking at home and in the community requires walking adaptability, defined as the ability to adjust the basic stepping pattern to meet environmental demands and task goals (e.g., obstacle negotiation, dual-tasking) (Balasubramanian, Clark, & Fox, 2014; Patla & Shumway-Cook, 1999). Individuals after stroke often demonstrate considerable difficulty with walking adaptability, even if they have relatively good recovery of steady state walking ability (Hill, Ellis, Bernhardt, Maggs, & Hull, 1997). In fact, individuals with post-stroke walking deficits frequently report the avoidance of conditions requiring adaptability (Robinson, Matsuda, Ciol, & Shumway-Cook, 2013). Subsequently, over one-third of individuals post-stroke are unable to walk in the community (Lord, McPherson, McNaughton, Rochester, & Weatherall, 2004) and three quarters report difficulty in an “outdoor community” setting (Robinson, Shumway-Cook, Ciol, & Kartin, 2011). Recovery of community mobility after stroke is critical because it is associated with the health-related benefits of increased physical activity, improved quality of life through participation in life roles and a decreased risk for depression (Carod-Artal, Egido, Gonzalez, & Varela de Seijas, 2000). While current physical therapy practice and rehabilitation emphasize the recovery of ambulation after stroke, minimal therapy time is spent on training the ability to adapt walking (Latham et al., 2005). To address this critical gap in the recovery of walking and design rehabilitation interventions that target community mobility after stroke, an important first step is to understand how stroke affects the ability to perform adaptations.

One component of walking adaptability that is underinvestigated in the post-stroke population is negotiation of uneven terrain. Walking on uneven terrain (e.g. gravel, grass) is unique because the surfaces are typically compliant, non-uniform and, therefore, unpredictable. The characteristics of uneven terrain, as well as the transitions between various surfaces, make anticipation of task demands particularly challenging. For instance, during walking on uneven terrain healthy adults modify both step parameters and limb kinematics to meet the demands of the task (MacLellan & Patla, 2006; Voloshina, Kuo, Daley, & Ferris, 2013; Wade, Redfern, Andres, & Breloff, 2010). Furthermore, healthy adults seem to rely on somatosensory inputs to adjust their walking strategy on uneven terrain, as a lack of visualization of the surface has no impact on step parameters (Rogers, Cromwell, & Grady, 2008; Schulz, 2011; Thies, Richardson, & Ashton-Miller, 2005). Overall, numerous strategies are used by healthy individuals during walking on uneven terrain to maintain stability and safety. Due to a critical gap in the understanding of mobility post-stroke, it is not known if people post-stroke would demonstrate similar adaptation strategies. It is likely that stroke-related impairments in motor, sensory and cognitive function will severely impair walking control during uneven terrain negotiation and adults post-stroke may adopt unique strategies.

To begin addressing this gap in the evidence, it is essential to have a good understanding of both the normal modifications used in uneven terrain negotiation and the implications of post-stroke walking deficits on these strategies. This step is critical prior to the development of research that investigates the changes that occur after stroke. Therefore, the first section is a scoping review which summarizes studies that have investigated gait modifications required for healthy adults to walk on uneven terrain. Scoping reviews employ a systematic search for evidence to address an explicit question, summarize findings in tabular form, and include a “narrative integration of the relevant evidence” (Dijkers, 2015). A search for relevant studies was conducted through PubMed and CINAHL using the search term “walking” with “uneven terrain,” “irregular surface,” or “compliant surface.” Additionally, the reference lists of the identified articles were explored for other pertinent studies. Articles were excluded if the paradigm involved a single unexpected perturbation, a slipping motion or a pathological population such as amputees or those with a neuropathy. The studies examined walking on a variety of surfaces (e.g. stones, foam and other combinations of materials) which were integrated into both overground and treadmill paradigms. Gait measures such as spatiotemporal parameters, lower extremity kinematics and muscle activity were examined. A table is included that summarizes the experimental design and key findings of each study (Table 1). This first section on gait modifications performed by healthy adults is separated into two categories: biomechanical and neuromuscular modifications. Subsequently, the second section provides a perspective on how these findings integrate with our understanding of common gait impairments after stroke. It concludes by providing insights into future steps needed to design investigations that will move the field towards enhanced knowledge about the mechanisms and recovery of the control of walking on uneven terrain in individuals post-stroke.

2. Biomechanical modifications during uneven terrain negotiation

2a. Step parameter modifications

When healthy adults walk on uneven terrain, changes in step parameters depend on the features of the uneven surface. For instance, walking on foam resulted in increased step length, width and time when compared to walking on level surface at the same speed (MacLellan & Patla, 2006). The wider and longer steps while walking on foam may provide an increased base of support making it easier to control the center of mass. While walking on two different surfaces, one composed of railroad ballast (irregularly shaped crushed stone) and the other of artificial grass over foam and small objects, a different adaptation pattern was observed; step time increased, similar to the response on foam, but step length decreased (Menant, Steele, Menz, Munro, & Lord, 2009; Wade et al., 2010). It is possible that the reduced speed associated with walking under these conditions may have influenced the step length. However, Wade et al. (Wade et al., 2010) described this strategy of shorter, slower steps as a “cautious gait” pattern. Walking with a shortened step length and increased step time could decrease the risk of slipping on surfaces where the foot has the potential to shift. Interestingly, unlike the overground walking studies that reported increases in step time, individuals adjusted with a decrease in step time as well as reduced step length during walking on an uneven treadmill surface (Voloshina et al., 2013). This strategy of reduced

step time and length may have emerged if the individuals were unfamiliar with a treadmill paradigm or because they were unable to alter their speed.

Another alteration found during negotiation of uneven terrain is increased movement variability, evidenced in parameters such as step length, width and time (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012; MacLellan & Patla, 2006; Menant, Steele, Menz, Munro, & Lord, 2011; Voloshina et al., 2013). Previously, increased step parameter variability has been associated with significant increases in the metabolic cost of walking (O'Connor, Xu, & Kuo, 2012). Therefore, the increased movement variability observed during uneven terrain negotiation is likely a contributing factor to the substantial increase in metabolic cost when walking on a surface with a small increase in surface variability (Voloshina et al., 2013). Without consistent and appropriate timing of events between lower extremities during the gait cycle, the energy requirement increases due to lost efficiency in the step to step energy transfer and joint work must increase to accommodate. For instance, if the work performed in the trailing leg during push-off does not equal the work of the leading leg during loading response, or if the events are not simultaneous, additional energy is required during single limb stance to maintain forward progression (Kuo, Donelan, & Ruina, 2005). Another likely explanation for the increase in metabolic cost during uneven terrain negotiation is the energy lost to the compliant environment, such as shifting of stones or sand under the feet, which reduces forward propulsion (Lejeune, Willems, & Heglund, 1998).

2b. Kinematic modifications

Similar to the changes observed in step parameters, healthy adults demonstrate modifications in gait kinematics to improve balance and prevent a fall when walking on uneven terrain. During stance, improved stability on an uneven surface is achieved by reducing the height of the center of mass (MacLellan & Patla, 2006) through a crouched position with increased hip and knee flexion (Gates et al., 2012). In addition, trunk and lower extremity adaptations assist in maintaining a steady head position to allow the visual and vestibular system to operate from a stable position and contribute more effectively to maintaining balance. Compared to walking on a level surface, walking on uneven terrain results in significantly increased pelvic accelerations (Menant et al., 2011; Menz, Lord, & Fitzpatrick, 2003a), but healthy young individuals demonstrate no significant change in head accelerations (Menz et al., 2003a). This suggests that trunk accommodations likely have a considerable role in successfully attenuating the perturbations created by the uneven terrain. In healthy adults who are older (aged 61–85), these trunk accommodations are impaired (Marigold & Patla, 2008; Menz, Lord, & Fitzpatrick, 2003b). Since the magnitude of accelerations increases exponentially as speed of walking increases (Menz et al., 2003a), the slower speed adopted by older adults on uneven terrain may be a strategy to maintain a tolerable level of head movement (Menz et al., 2003b). For example, the reduced speed adopted by older adults on uneven terrain has been found to result in lower pelvic acceleration magnitudes compared to younger individuals walking faster, but this reduction was not maintained at the head (Marigold & Patla, 2008). Instead, there was no significant difference between the groups in the magnitude of head accelerations in two planes, so the reduced speed was necessary to maintain the stable head position (Marigold & Patla, 2008).

Stability and safety improvements have shown to be achieved in swing through modifications that decrease the risk of tripping and slipping. Increased hip and knee flexion and dorsiflexion improves toe clearance, decreasing the risk of catching the toes and subsequently tripping on uneven terrain (Gates et al., 2012; MacLellan & Patla, 2006; Schulz, 2011). Though dorsiflexion increased when averaged across the gait cycle, decreased dorsiflexion was found in terminal swing resulting in a “flat-footed” approach rather than a true heel strike (Gates et al., 2012). Gates et al. (Gates et al., 2012) proposed that the flat-footed approach reduces the coefficient of friction required at the shoe-floor interface and therefore prevents slipping.

3. Neuromuscular modifications during uneven terrain negotiation

Neuromuscular modifications evident in healthy adults while walking on uneven terrain include increased muscle activity, greater contraction amplitude variability between steps and increased co-contraction in lower extremity muscles. These findings, measured with surface electromyography (EMG), are consistent with the kinematic changes, step to step variability and increased demands associated with walking on uneven terrain. For instance, the increased variability of muscle contraction amplitude is congruent with the increased variability in spatiotemporal parameters (Voloshina et al., 2013). Nearly all muscles demonstrated this increase in variability, although the increase was greater in thigh than leg muscles. Variability in thigh muscle activation may be related to the increased pelvic accelerations evident when walking on uneven terrain. As discussed earlier, increased movement variability correlates with increased energy expenditure while negotiating uneven terrain (Voloshina et al., 2013). Increased muscle activity and co-contraction also add to this increase in energy expenditure (Voloshina et al., 2013; Wade et al., 2010). Both mean and peak muscle activities increase and the contraction bursts demonstrate an earlier onset and longer duration compared to activity recorded during walking on level surface (Wade et al., 2010). Voloshina et al. (Voloshina et al., 2013) suggested that increases in muscle activity during ambulation on uneven terrain may be a reflection of the increased demand created by maintaining a more crouched position. The increased co-contraction recorded in both the knee flexors/extensors and ankle plantarflexors/dorsiflexors during stance supports this argument (Voloshina et al., 2013; Wade et al., 2010). Another possible explanation, proposed by Wade et al. (Wade et al., 2010), is that increased co-contraction stabilizes the joint in anticipation of the perturbations created by the surface and distributes the increased joint forces throughout the articular surface. Increased co-contraction of ankle invertors and evertors shortly after initial contact supports this reasoning (Wade et al., 2010). One exception to the increase in muscle activity has been identified by separating the analysis of muscle activity by gait phase, rather than averaging over the entire gait cycle. Tibialis anterior activity decreases in late swing, consistent with the biomechanical modification described earlier where dorsiflexion is reduced in late swing when approaching an unstable surface (Voloshina et al., 2013).

4. Implications of gait adaptations during uneven terrain negotiation for people after stroke

The evidence on healthy individuals serves as a basis for understanding the gait modifications required to successfully navigate uneven terrains. The following section aims to consider these findings from the perspective of known impairments after stroke. At this time no studies have directly assessed how individuals after stroke adapt their walking to uneven terrain. An understanding of both the modifications required and the specific post-stroke impairments that may interfere allows for an appreciation of the challenges this environment creates. The effect of this challenge is evident in the high proportion of individuals who require assistance and the use of an assistive device when walking outside of the home environment (Skolarus, Burke, & Freedman, 2014) as well as the increased falls after stroke (Jorgensen, Engstad, & Jacobsen, 2002).

A primary characteristic of post-stroke gait is asymmetry which is most apparent in the increased stance time on the non-paretic lower extremity and in the differences between paretic and non-paretic joint kinematics, particularly knee flexion in swing (Olney & Richards, 1996; Straudi et al., 2009). Much of this asymmetry stems from marked impairment in the ability to support one's own body weight during single limb stance and produce propulsion of the body during terminal stance and pre-swing (Chen, Patten, Kothari, & Zajac, 2005). Both decreased stance time and reduced control of single limb stance on the paretic side affect the individual's ability to generate non-paretic swing. On uneven terrain, this may reduce the non-paretic limb's capacity to produce the swing phase adaptations that are required for safe foot clearance. An individual after stroke also demonstrates reduced dorsiflexion, knee flexion and hip flexion in swing when ambulating on a level surface (Burdett, Borello-France, Blatchly, & Potter, 1988). This is problematic considering that healthy individuals utilize an increase in these parameters to successfully negotiate uneven terrain (Gates et al., 2012). In addition, gait speed on level surfaces is already reduced by 50% or more in individuals with moderate to severe impairments after stroke (Olney & Richards, 1996). It is therefore likely that gait speed will be further reduced on uneven terrain as post-stroke impairments limit adaptation to an unpredictable surface.

Changes in neuromuscular control after stroke will likely disrupt specific adaptation strategies used by healthy individuals. For instance, individuals after stroke demonstrate prolonged muscle activity, as well as an increase in the proportion of the gait cycle that antagonistic muscles are simultaneously active (Den Otter, Geurts, Mulder, & Duysens, 2007) and a reduction in the complexity of intermuscular coordination after stroke (Clark, Ting, Zajac, Neptune, & Kautz, 2010). The compliance and unpredictability of an uneven terrain surface will likely amplify the effects of these impairments in timing and coordination because the individual would be unable to produce the variable and task-specific modulation of muscle activity needed to adapt to the surface. In addition, the increased variability in spatiotemporal step characteristics present in steady state walking after stroke (Balasubramanian, Neptune, & Kautz, 2009) may amplify the increased gait variability on uneven terrain as reported in healthy individuals. Therefore, while increased muscle activation and greater co-contraction are may be necessary to safely and successfully

negotiate uneven terrain, individuals post-stroke already demonstrate reduced muscle activity and decreased co-contraction in the paretic limb during single limb support (Hirschberg & Nathanson, 1952; Lamontagne, Richards, & Malouin, 2000). Furthermore, deficits in trunk control and changes in posture after stroke (Karatas, Cetin, Bayramoglu, & Dilek, 2004) would likely compromise the ability to dampen accelerations at the head as was seen in older adults (Menz et al., 2003b). Reducing head movement during gait allows the visual and vestibular systems to operate from a more stable platform as they contribute to the maintenance of balance. This deficit may be particularly detrimental for those individuals with stroke that already have a reduction in visual, vestibular and/or somatosensory inputs to balance.

The multitude of gait adjustments required to walk on uneven terrain may also increase the demand for attentional resources for individuals post-stroke. This is evident from studies demonstrating increased cortical activity during the performance of walking tasks that require adaptability (Clark, Rose, Ring, & Porges, 2014; Koenraadt, Roelofsen, Duysens, & Keijsers, 2014; Meester, Al-Yahya, Dawes, Martin-Fagg, & Pinon, 2014). The complexity of the environment and the demands placed on the individual while walking on uneven terrain will likely result in heightened attentional demand and potential interference with control processes for any other simultaneous motor or cognitive task (Clark, 2015). This degrades performance and places the individual at increased risk for falling (Hyndman, Ashburn, Yardley, & Stack, 2006; Toulotte, Thevenon, Watelain, & Fabre, 2006).

Although walking on uneven terrain has not been investigated in individuals post-stroke, some insights can be gained from the performance changes after stroke in other walking tasks requiring adaptability. For example, while individuals post-stroke were able to successfully clear obstacles of two different heights, they completed this task with significantly less knee flexion and dorsiflexion and therefore relied on compensatory strategies to lift the foot (MacLellan, Richards, Fung, & McFadyen, 2013). There was also a decrement in performance as evidenced by the greater movement variability. Examination of step characteristics also revealed an ineffective strategy; participants had increased vertical foot clearance but reduced post-obstacle foot clearance (Said, Goldie, Patla, & Sparrow, 2001). Overall, it is likely that not only are these decrements in performance and compensations after stroke seen across varying walking adaptability tasks, but also may be particularly evident on uneven terrain given the demands of an unpredictable and variable surface.

Interestingly, despite the sensorimotor limitations post-stroke, it is also possible that when challenged to walk on uneven terrains, individuals post-stroke may actually be able to generate appropriate task-specific modifications required to successfully adapt their walking. In support of this concept, when children with spastic diplegia walked on uneven terrain, they demonstrated appropriate adaptations of greater hip flexion, knee flexion and dorsiflexion rather than the hypothesized compensatory strategy (Bohm, Hosl, Schwameder, & Doderlein, 2014). This task-specific and appropriate adaptation is notable since children with spastic diplegia exhibit reduced hip flexion, knee flexion and dorsiflexion during typical walking. Recently, a similar finding in people after stroke supports the idea that performance of walking tasks that require adaptability may elicit appropriate improvements

in muscle activation (Clark, Neptune, Behrman, & Kautz, 2016). Clark et al. (Clark et al., 2016) showed that, when performing a long step leading with the non-paretic leg, individuals consistently demonstrated an appropriately timed increase in plantarflexor activity to improve paretic leg propulsion and achieve an elongated step. Therefore, interventions that include uneven terrain negotiation may facilitate greater gains in performance than those focused only on steady state walking practice.

5. Conclusion

Successful navigation of uneven terrain requires a variety of adaptations to the basic stepping pattern. As demonstrated in healthy adults, these modifications improve safety by avoiding slips or trips and provide the needed muscle activity and movement variability to allow the body to progress across the surface with control. Many of these modifications require motor, sensory and cortical resources that are affected by stroke. These post-stroke impairments may interfere with the adaptation strategies required to safely and successfully negotiate uneven terrains. Therefore, people after stroke may use altered and ineffective strategies to walk on uneven terrain, resulting in greater mobility deficits on uneven terrain compared to their walking ability on level surfaces.

To advance the study of walking adaptability, and specifically that of uneven terrain negotiation, it is important to investigate and quantify step parameter and kinematic modifications used by individuals after stroke. Quantification of stroke-specific strategies may be challenging because of inter-individual variability of gait mechanics in individuals post-stroke. However, investigation and quantification of adaptability strategies for individuals post-stroke will enable development of specific intervention approaches that promote the recovery of uneven terrain negotiation. Studies should also move beyond biomechanical measures to quantify the neural control strategies, such as the role of cortical activity in the performance of necessary gait adaptations. These types of investigations can advance our understanding of walking adaptability after stroke and move us towards the goal of improved community mobility for this population.

Acknowledgments

This work was supported by the Foundation for Physical Therapy under the Florence P. Kendall Doctoral Scholarship; the National Institute of Child Health and Human Development under the Neuromuscular Plasticity Training Program (T32-HD043730); the National Center for Medical and Rehabilitation Research (NICHD) and National Institute for Neurological Disorders and Stroke under the Rehabilitation Research Career Development Program (K12-HD055929); the Department of Physical Therapy at the University of Florida; Brooks Rehabilitation; and the Brooks-PHHP Collaborative Research Fund.

References

- Balasubramanian CK, Clark DJ, Fox EJ. Walking adaptability after a stroke and its assessment in clinical settings. *Stroke Res Treat*. 2014; 2014:591013.doi: 10.1155/2014/591013 [PubMed: 25254140]
- Balasubramanian CK, Neptune RR, Kautz SA. Variability in spatiotemporal step characteristics and its relationship to walking performance post-stroke. *Gait Posture*. 2009; 29(3):408–414. DOI: 10.1016/j.gaitpost.2008.10.061 [PubMed: 19056272]

- Bohm H, Hosl M, Schwameder H, Doderlein L. Stiff-knee gait in cerebral palsy: how do patients adapt to uneven ground? *Gait Posture*. 2014; 39(4):1028–1033. DOI: 10.1016/j.gaitpost.2014.01.001 [PubMed: 24485919]
- Burdett RG, Borello-France D, Blatchly C, Potter C. Gait comparison of subjects with hemiplegia walking unbraced, with ankle-foot orthosis, and with Air-Stirrup brace. *Phys Ther*. 1988; 68(8): 1197–1203. [PubMed: 3399515]
- Carod-Artal J, Egido JA, Gonzalez JL, Varela de Seijas E. Quality of life among stroke survivors evaluated 1 year after stroke: experience of a stroke unit. *Stroke*. 2000; 31(12):2995–3000. [PubMed: 11108762]
- Chen G, Patten C, Kothari DH, Zajac FE. Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait Posture*. 2005; 22(1):51–56. DOI: 10.1016/j.gaitpost.2004.06.009 [PubMed: 15996592]
- Clark DJ. Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Front Hum Neurosci*. 2015; 9:246.doi: 10.3389/fnhum.2015.00246 [PubMed: 25999838]
- Clark DJ, Neptune RR, Behrman AL, Kautz SA. Locomotor Adaptability Task Promotes Intense and Task-Appropriate Output From the Paretic Leg During Walking. *Arch Phys Med Rehabil*. 2016; 97(3):493–496. DOI: 10.1016/j.apmr.2015.10.081 [PubMed: 26525528]
- Clark DJ, Rose DK, Ring SA, Porges EC. Utilization of central nervous system resources for preparation and performance of complex walking tasks in older adults. *Front Aging Neurosci*. 2014; 6:217.doi: 10.3389/fnagi.2014.00217 [PubMed: 25202270]
- Clark DJ, Ting LH, Zajac FE, Neptune RR, Kautz SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. *J Neurophysiol*. 2010; 103(2):844–857. DOI: 10.1152/jn.00825.2009 [PubMed: 20007501]
- Den Otter AR, Geurts AC, Mulder T, Duysens J. Abnormalities in the temporal patterning of lower extremity muscle activity in hemiparetic gait. *Gait Posture*. 2007; 25(3):342–352. DOI: 10.1016/j.gaitpost.2006.04.007 [PubMed: 16750632]
- Dijkers M. What is a scoping review? KT Update. 2015; 4(1) Retrieved from <http://ktdrr.org/products/update/v4n1/index.html>.
- Gates DH, Wilken JM, Scott SJ, Sinitski EH, Dingwell JB. Kinematic strategies for walking across a destabilizing rock surface. *Gait Posture*. 2012; 35(1):36–42. DOI: 10.1016/j.gaitpost.2011.08.001 [PubMed: 21890361]
- Hill K, Ellis P, Bernhardt J, Maggs P, Hull S. Balance and mobility outcomes for stroke patients: a comprehensive audit. *Aust J Physiother*. 1997; 43(3):173–180. [PubMed: 11676685]
- Hirschberg GG, Nathanson M. Electromyographic recording of muscular activity in normal and spastic gaits. *Arch Phys Med Rehabil*. 1952; 33(4):217–225. [PubMed: 14924804]
- Hyndman D, Ashburn A, Yardley L, Stack E. Interference between balance, gait and cognitive task performance among people with stroke living in the community. *Disabil Rehabil*. 2006; 28(13–14):849–856. DOI: 10.1080/09638280500534994 [PubMed: 16777772]
- Jorgensen L, Engstad T, Jacobsen BK. Higher incidence of falls in long-term stroke survivors than in population controls: depressive symptoms predict falls after stroke. *Stroke*. 2002; 33(2):542–547. [PubMed: 11823667]
- Karatas M, Cetin N, Bayramoglu M, Dilek A. Trunk muscle strength in relation to balance and functional disability in unihemispheric stroke patients. *Am J Phys Med Rehabil*. 2004; 83(2):81–87. DOI: 10.1097/01.phm.0000107486.99756.c7 [PubMed: 14758293]
- Koenraadt KL, Roelofsen EG, Duysens J, Keijsers NL. Cortical control of normal gait and precision stepping: an fNIRS study. *Neuroimage*. 2014; 85(Pt 1):415–422. DOI: 10.1016/j.neuroimage.2013.04.070 [PubMed: 23631980]
- Kuo AD, Donelan JM, Ruina A. Energetic consequences of walking like an inverted pendulum: step-to-step transitions. *Exerc Sport Sci Rev*. 2005; 33(2):88–97. [PubMed: 15821430]
- Lamontagne A, Richards CL, Malouin F. Coactivation during gait as an adaptive behavior after stroke. *J Electromyogr Kinesiol*. 2000; 10(6):407–415. [PubMed: 11102843]

- Latham NK, Jette DU, Slavin M, Richards LG, Procino A, Smout RJ, Horn SD. Physical therapy during stroke rehabilitation for people with different walking abilities. *Arch Phys Med Rehabil*. 2005; 86(12 Suppl 2):S41–S50. DOI: 10.1016/j.apmr.2005.08.128 [PubMed: 16373139]
- Lejeune TM, Willems PA, Heglund NC. Mechanics and energetics of human locomotion on sand. *J Exp Biol*. 1998; 201(Pt 13):2071–2080. [PubMed: 9622579]
- Lord SE, McPherson K, McNaughton HK, Rochester L, Weatherall M. Community ambulation after stroke: how important and obtainable is it and what measures appear predictive? *Arch Phys Med Rehabil*. 2004; 85(2):234–239. [PubMed: 14966707]
- MacLellan MJ, Patla AE. Adaptations of walking pattern on a compliant surface to regulate dynamic stability. *Exp Brain Res*. 2006; 173(3):521–530. DOI: 10.1007/s00221-006-0399-5 [PubMed: 16491406]
- MacLellan MJ, Richards CL, Fung J, McFadyen BJ. Use of segmental coordination analysis of nonparetic and paretic limbs during obstacle clearance in community-dwelling persons after stroke. *PM R*. 2013; 5(5):381–391. DOI: 10.1016/j.pmrj.2013.02.003 [PubMed: 23419745]
- Marigold DS, Patla AE. Age-related changes in gait for multi-surface terrain. *Gait Posture*. 2008; 27(4):689–696. DOI: 10.1016/j.gaitpost.2007.09.005 [PubMed: 17962018]
- Meester D, Al-Yahya E, Dawes H, Martin-Fagg P, Pinon C. Associations between prefrontal cortex activation and H-reflex modulation during dual task gait. *Front Hum Neurosci*. 2014; 8:78.doi: 10.3389/fnhum.2014.00078 [PubMed: 24600375]
- Menant JC, Steele JR, Menz HB, Munro BJ, Lord SR. Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. *Gait Posture*. 2009; 29(3):392–397. DOI: 10.1016/j.gaitpost.2008.10.057 [PubMed: 19041245]
- Menant JC, Steele JR, Menz HB, Munro BJ, Lord SR. Step time variability and pelvis acceleration patterns of younger and older adults: effects of footwear and surface conditions. *Res Sports Med*. 2011; 19(1):28–41. DOI: 10.1080/15438627.2011.534968 [PubMed: 21253974]
- Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait Posture*. 2003a; 18(1):35–46. [PubMed: 12855299]
- Menz HB, Lord SR, Fitzpatrick RC. Age-related differences in walking stability. *Age Ageing*. 2003b; 32(2):137–142. [PubMed: 12615555]
- O'Connor SM, Xu HZ, Kuo AD. Energetic cost of walking with increased step variability. *Gait Posture*. 2012; 36(1):102–107. DOI: 10.1016/j.gaitpost.2012.01.014 [PubMed: 22459093]
- Olney SJ, Richards C. Hemiparetic gait following stroke. Part I. Characteristics. *Gait Posture*. 1996; 4(2):136–148. doi: [http://dx.doi.org/10.1016/0966-6362\(96\)01063-6](http://dx.doi.org/10.1016/0966-6362(96)01063-6).
- Patla AE, Shumway-Cook A. Dimensions of mobility: defining the complexity and difficulty associated with community mobility. *J Aging Phys Activ*. 1999; 7(1):7–19.
- Robinson CA, Matsuda PN, Ciol MA, Shumway-Cook A. Participation in community walking following stroke: the influence of self-perceived environmental barriers. *Phys Ther*. 2013; 93(5): 620–627. DOI: 10.2522/ptj.20110217 [PubMed: 23329558]
- Robinson CA, Shumway-Cook A, Ciol MA, Kartin D. Participation in community walking following stroke: subjective versus objective measures and the impact of personal factors. *Phys Ther*. 2011; 91(12):1865–1876. DOI: 10.2522/ptj.20100216 [PubMed: 22003172]
- Rogers HL, Cromwell RL, Grady JL. Adaptive changes in gait of older and younger adults as responses to challenges to dynamic balance. *J Aging Phys Act*. 2008; 16(1):85–96. [PubMed: 18212397]
- Said CM, Goldie PA, Patla AE, Sparrow WA. Effect of stroke on step characteristics of obstacle crossing. *Arch Phys Med Rehabil*. 2001; 82(12):1712–1719. DOI: 10.1053/apmr.2001.26247 [PubMed: 11733887]
- Schulz BW. Minimum toe clearance adaptations to floor surface irregularity and gait speed. *J Biomech*. 2011; 44(7):1277–1284. DOI: 10.1016/j.jbiomech.2011.02.010 [PubMed: 21354576]
- Skolarus LE, Burke JF, Freedman VA. The role of accommodations in poststroke disability management. *J Gerontol B Psychol Sci Soc Sci*. 2014; 69(Suppl 1):S26–34. DOI: 10.1093/geronb/ gbu117 [PubMed: 25342820]

- Straudi S, Manca M, Aiello E, Ferraresi G, Cavazza S, Basaglia N. Sagittal plane kinematic analysis of the six-minute walk test: a classification of hemiplegic gait. *Eur J Phys Rehabil Med.* 2009; 45(3): 341–347. [PubMed: 19174756]
- Thies SB, Richardson JK, Ashton-Miller JA. Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. *Gait Posture.* 2005; 22(1):26–31. DOI: 10.1016/j.gaitpost.2004.06.004 [PubMed: 15996588]
- Toulotte C, Thevenon A, Watelain E, Fabre C. Identification of healthy elderly fallers and non-fallers by gait analysis under dual-task conditions. *Clin Rehabil.* 2006; 20(3):269–276. [PubMed: 16634347]
- Voloshina AS, Kuo AD, Daley MA, Ferris DP. Biomechanics and energetics of walking on uneven terrain. *J Exp Biol.* 2013; 216(Pt 21):3963–3970. DOI: 10.1242/jeb.081711 [PubMed: 23913951]
- Wade C, Redfern MS, Andres RO, Breloff SP. Joint kinetics and muscle activity while walking on ballast. *Hum Factors.* 2010; 52(5):560–573. [PubMed: 21186736]

Table 1

Studies investigating the effects of uneven terrain on gait

Article	Surface	Participants	Notable Features of Experimental Design	Major Findings on Adaptations to Uneven Terrain
Menz, Lord & Fitzpatrick, 2003a	Overground	Young adults n=30; 11M, 19F	Speed: Self-selected, six subjects performed at five different speeds	Increased step length and decreased cadence
	Artificial grass over foam and wooden blocks	Age: 29.0 ± 4.3 (22–39)	Standardized footwear: Oxford style lace up	Increased step time variability Increase in pelvic accelerations in all three planes
Menz, Lord & Fitzpatrick, 2003b	Overground	Young adults n=30; 11M, 19F	Speed: Self-selected	Older adults demonstrated decreased speed and step length
	Artificial grass over foam and wooden blocks	Age: 29.0 ± 4.3 (22–39)	Standardized footwear: Oxford style lace up	Older adults demonstrated reduced vertical accelerations of the head and pelvis No group difference in antero-posterior and medial-lateral accelerations in the uneven condition
		Healthy older adults n=30; 8M, 22F Age: 79.9 ± 3.0 (75–85)		No group difference in measure of smoothness (harmonic ratio) in acceleration patterns
Thies, Richardson & Ashton-Miller, 2005	Overground	Young women n=12	Speed: Self-selected	Increased step time was found on uneven terrain
	Carpet over triangular wooden prisms	Age: 22.2 ± 3.0	Standardized footwear: flat-soled athletic shoes	Increased variability of step width and time was found on uneven terrain
		Healthy older women n=12 Age: 70.2 ± 4.1	Harnessed for safety	Older women demonstrated significantly more step width variability
MacLellan & Patla, 2006	Overground	Young adults n=8; 3M, 5F	Speed: Self-selected	Increased step length, width and time Increased variability of step length, width and time
	Continuous medium density foam	Age: 20.6 ± 1.7	Recorded accelerating steps	Decreased height of center of mass Increased trunk pitch and toe clearance Reduced tibialis anterior activity in late swing, increased gastrocnemius and soleus activity during push-off, increased biceps femoris activity in late swing and weight acceptance
Marigold & Patla, 2008a	Overground	Young adults n=10; 5M, 5F	Speed: Self-selected	Older adults walked slower and had a shorter step length than younger adults in all conditions
	Combination of rocky, compliant,	Age: 26.1 ± 5.2 (20–37)	Harnessed for safety	Step width and variability of step width and length were smallest in the control condition

Article	Surface	Participants	Notable Features of Experimental Design	Major Findings on Adaptations to Uneven Terrain
	tilted, irregular and slippery sections	Healthy older adults n=10; 5M, 5F Age: 74.1 ± 7.2 (61–82)	Some trials involved slight change in direction of walking	Older adults had increased center of mass acceleration variability with increased trunk pitch and roll variability Center of mass acceleration variability in all three directions was smallest on level surface Older adults had a smaller medial-lateral head to trunk acceleration ratio, but larger vertical ratio
Menant et al., 2009	Overground	Young adults N=10; 4 M, 6F	Speed: Self-selected	Older adults walked slower with a lower cadence, shorter step length, smaller shoe-floor angle at heel strike, larger toe clearance and longer double-support time in all conditions Decreased walking speed, cadence, step length, double-support time, and heel horizontal velocity at heel strike on uneven terrain in all participants Increased step width and toe clearance on uneven terrain in all participants Older adults had a greater step width on the irregular surface
	Artificial grass over foam and wooden blocks	Age: 27.4 ± 2.5	Harnessed for safety	
		Older adults N=26; 14M, 12F Age: 78.5 ± 4.2	Also completed a wet linoleum floor condition and all conditions performed in eight shoe styles	
Menant et al., 2011	Overground	Young adults N=6; 1 M, 5F	Speed: Self-selected	Increased step time variability and pelvic acceleration in the AP and ML planes on uneven terrain Increased step time variability in young adults compared to older adults on uneven terrain Increased ML pelvic accelerations in older adults compared to young adults on uneven terrain
	Artificial grass over foam and wooden blocks	Age: 22.5 ± 2.5	Harnessed for safety	
		Older adults N=22; 10M, 12F Age: 78.4 ± 4.4	Also completed both conditions in eight shoe styles	
Wade et al., 2010	Overground	Young men n=20	Speed: Self-selected	Decreased speed, step length, and cadence Increased percentage of cycle in double support Mean and peak muscle activity increased Prolonged duration of muscle contraction Increased co-contraction
	Railroad ballast	Age: 22.98 (19–27)	Standardized footwear: steel-toed work boots	
			Full range of anthropometrics	
Schulz, 2011	Overground	Young adults n=14; 7M, 7F	Speed: Preferred, slower than preferred and as fast as safely possible	Increased minimum toe clearance with hidden obstacles > visible obstacles > no obstacles Increased hip flexion, knee flexion and dorsiflexion with hidden and visible obstacles > no obstacles
	Wooden triangular prism pieces affixed to plywood	Age: 27 ± 5 (20–35)	Harnessed for safety	

Article	Surface	Participants	Notable Features of Experimental Design	Major Findings on Adaptations to Uneven Terrain
			Visible and hidden obstacle conditions	
Gates et al., 2012	Overground	Young adults n=15; 12M, 3F	Speed: Normalized at Froude numbers 0.06, 0.10, 0.16 and 0.23	Increased variability of step length and width
	Loose river rocks	Age: 22 ± 5		Increased hip and knee flexion in swing and stance Increased dorsiflexion in swing except for increased plantarflexion prior to initial contact Decreased height of center of mass
Voloshina et al., 2013	Treadmill	Young adults n=11; 7M, 4F	Speed: Normalized at 1.0 m/s on treadmill, within 10% overground	Decreased step length and time Increased variability of step length, width and time
	Uneven wooden blocks with attached foam	Age: 22.9 ± 2.8		Qualitative increase in hip and knee flexion range of motion Increased mean muscle activity (proximal leg muscles) Increased co-contraction Increased variability of muscle activity
			Standardized footwear: rubber-soled socks	