Age-related changes to composite lower extremity kinetics and their constituents in healthy gait: A perspective on contributing factors and mechanisms

Shawn C. Sorenson 1, Sean P. Flanagan 2

1 Division of Biokinesiology and Physical Therapy, University of Southern California, USA 2 Department of Kinesiology, California State University, Northridge, USA

Abstract

This perspective examines the isolated effect of healthy aging on combined lower extremity and individual joint kinetics during gait, as well as mechanisms for this adaptation. Older adults redistribute neuromuscular effort from the ankle to the hip without changes in overall lower extremity kinetics. This kinetic effect parallels kinematic alterations to stride characteristics and body segment geometry. Evidence suggests that both kinetic and kinematic factors may drive observed adaptations with aging. There is stronger support for the influence of kinematic effects, including increased hip flexion, body center of mass repositioning, and balance-driven control strategies. These data indicate that appropriate interventions may alter age-related changes. Further, insights gained from the study of healthy aging may be applied to better understand the independent effects of other adaptive stimuli such as degeneration, acute injury, or exercise. Finally, this analysis demonstrates that due consideration of task sensitivity, kinematic/kinetic interdependence, and conscious/unconscious motor control is critical to any biomechanical investigation of an aging population.

Introduction

Aging brings about both kinematic (spatio-temporal characteristics of motion) and kinetic (forces responsible for motion) changes in gait. Understanding the mechanisms behind these changes is key to developing interventions that could slow, or even possibly reverse, them. For example, programs aimed at targeting kinetic factors (such as strength training) may not be optimal if the changes are caused primarily by kinematic factors. The fact that the two factors are interrelated (kinematic changes alter the kinetics and vice versa) leads to a “chicken or the egg” scenario: do kinematic factors drive kinetic changes during gait, or do kinetic factors drive kinematic changes? This perspective will address this question, which has implications for clinical interventions and future scientific investigations.

Normal gait provides an ideal context to evaluate baseline adaptations due to aging. It is a common, everyday activity that is frequently used to evaluate overall health and functional status. Unfortunately the dynamic analysis of gait in an aging paradigm is often confounded by a change in the fundamental nature of the task. Specifically, older adults tend to choose a slower gait velocity in comparison to young adults. Thus, while one may observe discrepancies in whole body or joint dynamics between younger and older people, it is unclear whether those differences are due
to age-related neuromuscular adaptation, or simply the choice to walk at a different speed [1]. While this “choice” in itself may be influenced by age-related adaptation, this cannot be verified without evidence from investigations that control for gait velocity.

Two studies have attempted to address this deficiency by examining gait at similar speeds for healthy young and older adults. DeVita et al. [1] examined young and elderly adults walking at the same speed. Savelberg et al. [2] performed a similar study that also evaluated the influence of activity. In both studies, age-related changes to lower extremity kinematics and kinetics were observed at the whole body and individual joint levels (Fig. 1 and 2; Table 1).

![Figure 1](image1.png)

**Figure 1.** Support, hip, knee, and ankle net joint moment curves for young and elderly adults in normal, 1.48 m/s gait. Positive values indicate net internal extensor/plantarflexor moments.

From DeVita et al. (1). Used with permission from the American Physiological Society.

![Figure 2](image2.png)

**Figure 2.** Support, ankle, knee, and hip net joint moment curves for young and elderly adults in normal, speed-controlled gait.

YA = Young Active, YI = Young Inactive, OA = Old Active, OI = Old Inactive. Positive values indicate net internal extensor/plantarflexor moments.

Reprinted from Savelberg et al. (2) with permission from Elsevier.
Table 1. Summary of observed age-related kinematic and kinetic changes in normal gait.
Adapted from DeVita et al. (1) and Savelberg et al. (2).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DeVita et al. (2000)</th>
<th>Savelberg et al. (2007)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait Velocity</td>
<td>No change</td>
<td>No change²</td>
</tr>
<tr>
<td>(Controlled)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Length</td>
<td>Reduced</td>
<td>Reduced</td>
</tr>
<tr>
<td>Cadence</td>
<td>Increased</td>
<td>Reduced</td>
</tr>
<tr>
<td>% Gait Cycle in</td>
<td>Increased</td>
<td>n/a</td>
</tr>
<tr>
<td>Stance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Hip Flexion</td>
<td>Increased</td>
<td>n/a</td>
</tr>
<tr>
<td>Average Ankle Dorsiflexion</td>
<td>Reduced</td>
<td>n/a</td>
</tr>
<tr>
<td>Hip ROM</td>
<td>Increased</td>
<td>n/a</td>
</tr>
<tr>
<td>Ankle ROM</td>
<td>Reduced</td>
<td>Increased</td>
</tr>
<tr>
<td>Support Impulse</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>Hip Extensor Impulse</td>
<td>Increased</td>
<td>Increased</td>
</tr>
<tr>
<td>Hip Flexor Impulse</td>
<td>Reduced</td>
<td>No change</td>
</tr>
<tr>
<td>Knee Extensor Impulse</td>
<td>Reduced</td>
<td>Reduced</td>
</tr>
<tr>
<td>Ankle Plantarflexor Impulse</td>
<td>Reduced</td>
<td>Reduced</td>
</tr>
</tbody>
</table>

¹ Based on findings for young and old active groups
² Normalized for leg length

These findings are summarized as follows:

**Kinematic changes:** DeVita et al. reported identical gait velocities between groups, whereas Savelberg et al. reported similar velocities after adjusting for group differences in leg length. Both studies showed reduced step length for older adults, but one [1] reported higher cadences while the other [2] reported lower. As gait velocities – but not step length or cadence parameters – were normalized to leg length in the latter study, it is possible that this effect or other methodological differences explain the discrepancy. DeVita et al. reported an age-related increase in proportion of the gait cycle spent in stance vs. swing, along with a stance position that was on average more flexed at the hip, and more plantar flexed at the ankle. The flexed hip position was related to forward lean of the trunk. Older adults exhibited greater range of motion (ROM) at the hip joint, and lesser ROM at the ankle. This is in contrast to the findings of Savelberg et al., who reported an age-related increase in ankle ROM.

**Kinetic changes:** The focus of both studies is on a comparison of the support moment (algebraic sum of the hip, knee and ankle net joint moment), time-integrated support moment (support impulse), and their constituents. DeVita et al. showed similar support moment and impulse throughout the gait cycle for younger and older adults. Savelberg et al. reported the same result for active younger and older adults, but showed reduced support moment and impulse for inactive older adults, implying an important activity influence independent of aging. Specifically, reduced support impulse suggests a modification in overall lower extremity dynamics that is not evident from aging alone.

At the hip joint, DeVita et al. demonstrated higher net joint moment (NJM) extensor impulse and lower flexor impulse during stance for older adults. This was due to changes in both the magnitude and temporal characteristics of the respective hip NJM curves. Older adults had higher peak extensor NJM, and lower peak flexor NJM. They also spent a greater proportion of stance in a net extensor moment compared to a net flexor moment.

At the knee, DeVita et al. showed a lower extensor NJM impulse during stance for older adults. These changes appear to be due primarily to a reduction in the magnitude of the knee NJM, as opposed to significant temporal effects. Savelberg et al. showed a similar result, with age-related reductions in extensor NJM and impulse. Both studies showed lower peak plantar flexor NJM and impulse for older adults. Again, these reductions appear to be due to NJM reductions in the absence of temporal shifts.

Similar support impulse with variable joint contributions led authors of both studies to conclude that, while healthy aging does not modify overall dynamics of the lower extremity, it does bring about a substitution pattern in which older adults redistribute neuromuscular effort from the ankle to the hip.

**The Ubiquitous “Chicken or the Egg?”**

It is critical to note that the observed kinematic and kinetic changes are inherently interdependent. A change to the kinematic pattern necessitates a change in kinetics, and vice versa. The fundamental challenge
in understanding the mechanism is identifying which of the two is primarily responsible. As such, we consider the following two possibilities:

a) Age brings about a change in kinetic strategy, due (for example) to reductions in the ability to generate joint moments. This kinetic strategy subsequently drives adapted kinematics.

b) Age brings about a change in kinematic strategy, due (for example) to an altered motor program. This kinematic strategy subsequently drives adapted kinetics.

Evidence for the chicken: Age-related declines in joint moment capacity drive kinematic changes

DeVita et al. hypothesized that aging causes a preferential decline in plantar flexor muscle function as compared to the hip extensors. As the ability to generate torque at the ankle was reduced by this decline, older adults developed a kinetic strategy that transferred relatively higher loads to the hip extensor musculature. This study showed that the hip produced relatively higher proportions of the support impulse as compared to the ankle in older individuals. While Savelberg, et al. had similar findings, the fact that inactive older adults demonstrated significantly different support moments led the authors to conclude that both age and activity effects on muscle strength are important considerations.

There is significant evidence to support a decline in plantar flexor muscle strength with age. Christ et al. [3] reported an approximately 40% decline in maximal isometric plantar flexor force production for women aged 25-74y, while Thom et al. [4] showed a similar isometric torque deficit in men aged 19-82y, with larger deficits at progressively higher isokinetic velocities. Gajdosik et al. [5] showed torque reductions of approximately 40-45% for women aged 20-84y at isokinetic velocities of 30-180°/s.

However, comparable strength reductions have also been reported for the knee and hip extensors. Macaluso et al. [6] showed a reduction of approximately 40% in isometric knee extension torque for women aged 23-70y. Lanza et al. [7] found an average isometric knee extensor torque deficit of approximately 20% for men and women aged 26-72y, and also showed this value to be highly dependent on the knee angle. At 90° of knee flexion, no significant difference was found for older vs. younger adults, whereas a 52% difference was observed at 140° of flexion. Lanza et al. also reported isokinetic measures, with an average age-related reduction of approximately 30% across all velocities. Dean et al. [8] measured isometric strength of the hip extensors in women aged 23-75y, and reported 30% lower torque for older participants.

While reported strength deficits at the ankle joint are, in general, higher than those at the knee and hip, they are not dramatically so. The variability in reported strength measures reduces confidence in generalizing these trends to specific study populations and/or tasks. Further, caution must be exercised when comparing NJM as determined by inverse dynamics with strength measures alone. It has been noted that coactivation may influence reported strength measures [6], and that this coactivation is variable between joints [9]. Coactivation is certainly task and subject dependent. As neither NJM nor strength measures alone provide information about relative levels of coactivation, inherent discrepancies must be expected. It should be noted as well that observed NJM during gait might significantly exceed maximal efforts as estimated by strength tests. DeVita et al. [1] report a maximum ankle MJ during gait of approximately 130 Nm for young adults, and 110 Nm for older adults. These peak values occurred at approximately isometric or low velocity isokinetic conditions. Yet they are notably higher than maximum plantar flexor torques estimated by dynamometry under similar conditions. Thom et al. [4] reported maximum isometric plantar flexor torques of approximately 120 Nm and 75 Nm for younger and older men, respectively. Gajdosik et al. [5] reported maximum values of approximately 80 Nm and 50 Nm for younger and older women at an isokinetic condition of 30°/s.

Despite these limitations, comparison shows that the ratio of peak extensor and plantar flexor MJ to maximum isometric torque increases for older versus younger adults at both the ankle and hip joints (Table 2). This increase is larger at the ankle, suggesting that older adults actually prefer to utilize additional plantar flexor capacity as compared to hip extensor capacity.

Evidence for the chicken: Age-related declines in joint moment capacity drive kinematic changes

DeVita et al. hypothesized that aging causes a preferential decline in plantar flexor muscle function as compared to the hip extensors. As the ability to generate torque at the ankle was reduced by this decline, older adults developed a kinetic strategy that transferred relatively higher loads to the hip extensor musculature. This study showed that the hip produced relatively higher proportions of the support impulse as compared to the ankle in older individuals. While Savelberg, et al. had similar findings, the fact that inactive older adults demonstrated significantly different support moments led the authors to conclude that both age and activity effects on muscle strength are important considerations.

There is significant evidence to support a decline in plantar flexor muscle strength with age. Christ et al. [3] reported an approximately 40% decline in maximal isometric plantar flexor force production for women aged 25-74y, while Thom et al. [4] showed a similar isometric torque deficit in men aged 19-82y, with larger deficits at progressively higher isokinetic velocities. Gajdosik et al. [5] showed torque reductions of approximately 40-45% for women aged 20-84y at isokinetic velocities of 30-180°/s.

However, comparable strength reductions have also been reported for the knee and hip extensors. Macaluso et al. [6] showed a reduction of approximately 40% in isometric knee extension torque for women aged 23-70y. Lanza et al. [7] found an average isometric knee extensor torque deficit of approximately 20% for men and women aged 26-72y, and also showed this value to be highly dependent on the knee angle. At 90° of knee flexion, no significant difference was found for older vs. younger adults, whereas a 52% difference was observed at 140° of flexion. Lanza et al. also reported isokinetic measures, with an average age-related reduction of approximately 30% across all velocities. Dean et al. [8] measured isometric strength of the hip extensors in women aged 23-75y, and reported 30% lower torque for older participants.

While reported strength deficits at the ankle joint are, in general, higher than those at the knee and hip, they are not dramatically so. The variability in reported strength measures reduces confidence in generalizing these trends to specific study populations and/or tasks. Further, caution must be exercised when comparing NJM as determined by inverse dynamics with strength measures alone. It has been noted that coactivation may influence reported strength measures [6], and that this coactivation is variable between joints [9]. Coactivation is certainly task and subject dependent. As neither NJM nor strength measures alone provide information about relative levels of coactivation, inherent discrepancies must be expected. It should be noted as well that observed NJM during gait might significantly exceed maximal efforts as estimated by strength tests. DeVita et al. [1] report a maximum ankle MJ during gait of approximately 130 Nm for young adults, and 110 Nm for older adults. These peak values occurred at approximately isometric or low velocity isokinetic conditions. Yet they are notably higher than maximum plantar flexor torques estimated by dynamometry under similar conditions. Thom et al. [4] reported maximum isometric plantar flexor torques of approximately 120 Nm and 75 Nm for younger and older men, respectively. Gajdosik et al. [5] reported maximum values of approximately 80 Nm and 50 Nm for younger and older women at an isokinetic condition of 30°/s.

Despite these limitations, comparison shows that the ratio of peak extensor and plantar flexor MJ to maximum isometric torque increases for older versus younger adults at both the ankle and hip joints (Table 2). This increase is larger at the ankle, suggesting that older adults actually prefer to utilize additional plantar flexor capacity as compared to hip extensor capacity.
Table 2. Peak lower extremity extensor/plantarflexor net joint moments compared to maximum isometric torque for young and elderly adults in normal 1.48 m/s gait

<table>
<thead>
<tr>
<th>Joint</th>
<th>Peak NJM (Young)</th>
<th>Maximum Isometric Torque (Young)</th>
<th>NJM % of Maximum Torque (Young)</th>
<th>Peak NJM (Elderly)</th>
<th>Maximum Isometric Torque (Elderly)</th>
<th>NJM % of Maximum Torque (Elderly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle</td>
<td>130</td>
<td>85</td>
<td>153%</td>
<td>110</td>
<td>55</td>
<td>200%</td>
</tr>
<tr>
<td>Knee</td>
<td>60</td>
<td>130</td>
<td>46%</td>
<td>40</td>
<td>80</td>
<td>44%</td>
</tr>
<tr>
<td>Hip</td>
<td>100</td>
<td>110</td>
<td>91%</td>
<td>95</td>
<td>75</td>
<td>127%</td>
</tr>
</tbody>
</table>

1 Estimated from DeVita et al. (1)
2 Estimated from Christ et al. (3), Dean et al. (8), Kubo et al. (25), Lanza et al. (7), Macaluso et al. (6), and Thom et al. (4)
All NJM and torque values are expressed in N*m units

A preferential plantar flexor strength decline also fails to explain why the hip extensors, as opposed to the knee extensors, would necessarily experience increased loading as a result of reduced plantar flexor strength. Both muscle groups have the capability to provide support via rotation of the thigh in the sagittal plane. In the absence of dramatic differences in strength decline, it is unclear why the hip extensors would be preferred.

In summary, while it is clear that aging brings about a deficit in plantar flexor moment capacity, it is not clear that this change is preferential in comparison to the knee and/or hip extensors, or that this decline necessarily dictates a modification in gait strategy.

**Evidence for the egg: Age-related kinematic strategies drive changes to joint kinetics**

The other possibility is that kinematic changes, unrelated to lower extremity joint moment capacity, dictate adaptations in lower extremity joint kinetics. These adaptations may arise from at least several causes, including:

a) Alterations to relative segment positioning due to passive constraints in the lower extremity and/or musculotendinous adaptations in the upper body

b) Conscious or unconscious alterations to dynamic gait control strategy

Both situations involve dynamic repositioning of the joint centers relative to the body center of mass (BCM), the base of support, and/or the ground reaction force vector. As NJMs are determined as a function of this geometry, joint moment redistributions may readily occur independent of any change in maximal joint torque capacity [10,11]. Numerous possibilities for this repositioning exist, including forward lean of the trunk, anterior tilt of the pelvis, kyphosis, and lumbar lordosis [11,12].

Kinematic changes at the hip are of particular interest due to the pattern of hip extensor/flexor NJM reported by DeVita et al. [1]. Unlike the ankle and knee – which showed reduced NJM magnitudes for older subjects without notable changes to the temporal characteristics of the NJM curves – the hip NJM showed an age-related alterations in both magnitude and timing (Fig. 1). Older adults had higher extensor NJMs, lower flexor NJMs, and maintained a net extensor moment much later into stance. The result is an upward shift of the NJM vs. time curve that dramatically affects the time component of NJM impulse, increasing extensor impulse and reducing flexor impulse. This pattern is inconsistent with relative age-related strength deficits for hip extensors (-30%) and flexors (-20%) as reported by Dean et al. [8] that would suggest an adaptation in the opposite direction. Rather, the observed results may be more consistent with a fundamental change in body positioning strategy.

Recall that DeVita et al. [1] reported a more flexed hip angle throughout stance in the elderly group. This adaptation, even in the presence of reduced peak hip extension, allowed for greater total ROM. A more flexed hip posture due to forward lean of the trunk and/or anterior pelvic tilt has been reported in other studies on elderly gait [12,13]. Kerrigan et al. [13] hypothesized that hip flexion contractures and
associated pelvic tilt fundamentally influence gait characteristics including step length, hip ROM, and hip NJM. A follow-up study [14] demonstrated that elderly adults who performed a hip flexor stretching program showed tendencies toward increased peak hip extension and flexor moment, and reduced anterior pelvic tilt. The stretching program also resulted in changes to ankle dynamics, notably an increase in peak plantar flexion angle, and a tendency toward increased plantar flexor work. This adaptive training response shows a partial reversal of the age-related changes reported by DeVita et al. [1], suggesting that a proximal impairment at the hip may in fact be the underlying cause of secondary changes elsewhere in the lower extremity or at the whole body level [15].

In a study of older adults with a history of falls compared to those without, Kerrigan et al. [16] demonstrated a remarkably similar shift in the hip NJM profile to that reported by DeVita et al. for older versus younger adults (Fig. 3). Walking at slightly higher speed with greater cadence, fallers had increased extensor NJM in early stance – persisting later into the stance phase – followed by reduced flexor NJM. Importantly, fallers also showed a tendency toward reduced plantar flexor power in late stance. Though this study did not report NJM impulse, the shape of the NJM curves indicates that elderly fallers as compared to non-fallers demonstrate a similar substitution pattern as older versus younger healthy adults. This offers evidence that dynamic control strategies have an important effect on NJM distribution. This is supported as well by a study by Lewis and Ferris [17], in which young adults showed modified ankle and hip kinetics as a result of instruction to increase or decrease ankle push-off.

In general, older adults choose shorter step length, larger relative stance time, and similar cadence compared to younger adults when walking at self-selected speeds [1,12,18]. When asked to walk faster, older adults increase cadence but not step length, whereas younger people achieve higher velocities by increasing both parameters [12,19]. This behavior suggests that step length is the controlling factor in age-related gait adaptation. Reduced step length may be due to limitations imposed by hip flexor contracture and/or pelvic dynamics as discussed above [12]. Alternatively, it may be part of a strategy that reduces excursion of the BCM with respect to the base of support, thereby improving dynamic stability and/or reducing the fear of falling [20,21]. While much work has been done to illustrate the influence of ankle plantar flexion on step length [13], this too may be the purposeful result of a balance control strategy [12,18]. Modified whole body dynamic control in response to fall risk may explain the observations of DeVita et al., who reported step length reduction in older adults with corresponding increases in cadence to maintain comparable velocity.

![Figure 3. Hip net joint moment curves for fallers (solid lines) versus nonfallers (dashed line) in comfortable (bold solid line) and fast (thin solid line) gait.](image)

Average gait speeds were 1.21 m/s (nonfallers, comfortable), 1.34 m/s (fallers, fast), and 0.89 m/s (fallers, comfortable). Positive values indicate a net internal extensor moment. Reprinted from Kerrigan et al. (16) with permission from Elsevier.

Requiao et al. [22] showed that increased cadence increases muscular utilization of both the ankle plantar flexors and hip extensors, with a more pronounced change at the hip. This suggests that higher cadence may dictate greater emphasis on hip musculature. The result must be interpreted with caution, as increased cadence did not occur independently of step length. In fact, both step length and cadence increased to produce higher gait velocity. However, the 110% increase in velocity from slowest
to fastest speed resulted from a 73% increase in cadence, and a 22% increase in step length, suggesting that the observed NJM changes are more likely due to cadence than step length effects.

Gait alterations have also been shown due to anticipated slip risk in healthy adults walking across known dry and slippery surfaces [23,24]. Changes include shorter stride length, reduced peak ankle and knee NJM, and changes in both the magnitude and temporal profile of hip NJM. These studies unfortunately do not distinguish whether the observed dynamics are due simply to reduced gait speed or to an altered control strategy in response to the slip/fall risk. However, together with data from Requiao et al. [22], they show that a control strategy emphasizing increased cadence and reduced step length to achieve the same velocity may influence the distribution of lower extremity joint kinetics. Further, they demonstrate that healthy older adults compared to younger adults show similar gait alterations as people walking across known slippery versus stable surfaces. This suggests an association between modified stability control strategies during gait and healthy aging.

It is clear that a number of underlying kinematic mechanisms may contribute to age-related joint kinetic adaptations as observed by DeVita et al. While none of these mechanisms stand alone as a definitive explanation, together they appear to offer substantial evidence toward a principle kinematic effect.

The weight of the evidence indicates that the predominant factors are those related to kinematic alterations to the gait pattern, including modified hip flexion angle and balance-driven control strategies. The joint kinetics are a consequence of these adaptations. This is supported principally by the observation that reversal of the joint kinetic patterns is possible when kinematic variables change independently of strength. Opportunities for improvement of our knowledge exist in at least several areas. First, better assessments of maximal joint torque capacity in comparison to observed NJMs would improve understanding of how age-related strength changes impact gait. The work of Requiao et al. [22] provides a fine example in that reported strength measures are a function of both joint angle and velocity. This provides a more robust baseline for comparison than a single isometric or isokinetic test. Additional work is also required to explain the discrepancy between maximal torque capacity as measured during strength tests and higher NJMs computed via inverse dynamics. Second, studies that evaluate the effects of step length and cadence under constant gait velocity would be extremely valuable. These studies may explicitly seek to control step length and cadence, or alternatively probe their underlying causes. For example, healthy subjects might be asked to walk normally for one trial, and carefully – with concern for balance – in another, while maintaining the same speed. A cross-sectional approach using a study population of different ages could be used to evaluate the effects of age on the dynamic response. Third, the formal validation of support moment and impulse as appropriate composite measures for gait is required to demonstrate their utility compared to alternative measures. Finally, long-term prospective studies that characterize gait adaptations in the same population would help to isolate strictly age-related adaptations.

**Conclusions**

Recall that our principle objective in studying age-related changes to gait dynamics was to assess the impact of this “natural” adaptation on joint kinetic measures. First, the results of our perspective indicate that in speed-controlled gait, healthy aging brings about a redistribution of muscular effort primarily
from the ankle to the hip without a change in overall lower extremity dynamics. As this redistribution occurs in the absence of known pathology, training, or acute stimuli, we may conclude that age is an important control parameter in studying these other adaptations. One of the more compelling lines of future research is examination of intervention paradigms that accelerate or inhibit the natural aging process.

Second, we have shown that joint kinetics have a high degree of task sensitivity. Modification of parameters such as gait speed, step length, or cadence, has a strong influence on results. As such, it is important in any comparative joint kinetic study to ensure that the selected performance metric is specific enough to isolate the outcome variables of interest.

Third, we have illustrated that evaluation of constituent joint kinetics absolutely requires a parallel assessment of related whole-body and joint kinematics. Motion of the BCM relative to joint centers is critical in evaluating mechanisms of joint level dynamics. Changes to observed kinematics at any level require an investigation of their sources and an assessment of their impact on the kinetic result.

Next, we have highlighted the interdependence of the kinetic chain. Joints do not function in isolation. Rather, the movement of one joint indirectly impacts others. In general this logic extends to joint systems such as the lower or upper extremity. While it is not practical to evaluate full body dynamics in every situation, a minimum qualitative understanding is necessary to appreciate potential influences on the region of interest.

Finally, we have demonstrated that dynamic adaptations may be a function of passive constraints and/or active moderation from conscious or unconscious motor inputs, including dynamic stability control. These inputs are highly context sensitive. That is to say that when one’s perception of task requirements changes, performance might change even if the task itself and the ability to perform the task are identical.

Acknowledgements

The authors thank Kornelia Kulig, Ph.D. and George J. Salem, Ph.D. for their contributions to this manuscript.

References

12. Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA, Collins JJ. Biomechanical gait alterations independent of


