**Osteoarthritis in Amputees: Prevalence, Etiology, & Intervention**

**Introduction**

Every day the number of individuals with an amputation increases. Additionally, a number of musculoskeletal conditions may occur secondary to amputation. As this patient population increases, so does the need for a more in depth and comprehensive understanding of musculoskeletal conditions associated with amputation to prevent a reduction in quality of life. The purpose of this article is to review the current literature on the prevalence, contributing factors, and prevention and intervention for OA in the intact limb of lower extremity amputees.

**Prevalence of Osteoarthritis in Amputees**

Currently, 1.7 million individuals in the United States have had an amputation with another 185,000 occurring each year. 1,2 Lower extremity amputees face a number of musculoskeletal conditions secondary to amputation that can increase disability. Osteoarthritis is common a musculoskeletal condition that arises in lower extremity amputees following long-term prosthetic use. 3 Vincent et al reported that, “osteoarthritis is the most frequent cause of disability in the United States.” 4 Several reports indicate that OA is more prevalent in lower extremity amputees than the general population. 5-7 Such limitations often lead to poor mobility and, in turn, decreased activity and quality of life. 8

OA involves a chronic degeneration of articular cartilage and periarticular bone remodeling that causes joint pain and stiffness and results in functional impairment. 8 Morgenroth et al state, “the etiology of OA is thought to be multifactorial: a combination of potentially modifiable factors related to abnormal joint mechanics, superimposed on underlying risk factors including age, gender, race/ethnicity, and other specific genetic factors.” 8 Amputees are more likely to have OA in their intact limb compared to the amputated limb, and transfemoral amputees are at a greater risk than transtibial amputees. 8,9 The prevalence of knee OA in amputees has been reported as 28.3% for men and 22.2% for women, whereas the prevalence in able-bodied men was 1.58% and 1.33% for women. 5 The prevalence of hip OA was also greater in male and female amputees, 15.3% and 11.1%, respectively, compared to 1.13% of able-bodied men and 0.98% of able-bodied women. 5

**Contributors to OA in Amputees**

Amputees are at a greater risk for developing OA from altered gait mechanics with prosthetic use. A majority of amputees who use prostheses for ambulation do so with at least one gait deviation, either from poor prosthetic fit, poor gait training, or bad habits. 3 Amputees often ambulate with an increased demand on the intact limb from temporal asymmetries, asymmetrical muscle activity, and increased joint loading with compensations, all of which can result in degenerative changes at the hip and/or knee.

Temporal Asymmetries

The results of numerous studies indicate that amputees have greater stance time and shorter swing time for their intact limb. 3,10-12 Sanderson et al reported amputees had statistically greater stance times on the intact limb at gait speeds of 1.2 m/s and 1.6 m/s (798ms and 667ms) compared to the prosthetic limb (758ms and 624 ms). 10 Further, at both 1.2 m/s and 1.6 m/s, the intact limb had shorter swing times (427 ms and 394ms) compared to the prosthetic limb (468 ms and 410 ms). 10 When compared to able-bodied subjects, amputees had greater stance and shorter swing times on the intact limb indicating asymmetries and a greater demand on the intact limb than in normal walking. 10 Dingwell et al also reported significant differences in temporal asymmetries between amputees and able-bodied subjects with percent stance time, push-off force, and single support time being 4.6 times greater for amputees compared to able-bodied subjects. 11Kovac et al also reported amputees’ prosthetic limb had increased swing time and decrease stance time compared with able-bodied gait. 12

Sixty-four percent of amputees report more dependence on their intact lower extremity than the amputated extremity during daily activities. 3 This is, in part, shown by the increase in stance time on the intact lower extremity. An increase in stance time on the intact limb suggests increased joint loading at the hip and knee. Burke et al suggest that the increase in stance time for the intact limb could be one contributor to an increase in prevalence of hip and knee OA in lower extremity amputees. 6

Strength Asymmetries

Amputees’ preference of the intact limb over the prosthetic limb for weight bearing further exacerbates articular cartilage degeneration through muscle strength asymmetries. Amputees commonly have atrophy of muscles on the prosthetic limb side and hypertrophy of muscles on the intact side from increased use of the intact limb and lack of use in the prosthetic limb. 13 An increase in muscle activity on the intact limb will increase the contact force and pressure at the joints of intact limb, and may contribute to the development of OA. The increase in intact limb dependence could be attributed to lack of confidence in the prosthesis or decreased proprioception in the residual limb. 14 Isakov et al reported statistically significant differences in hamstring and quadriceps strength measured concentrically, eccentrically, and isometrically with muscles of the intact limb being significantly stronger. 15 Nadollek et al reported a correlation between increased stance time on the residual limb and stronger hip abductors, indicating improved strength symmetry was related to improved stance symmetry. 14 Lloyd et al also examined strength asymmetry for correlations. 13 External knee adduction moment loading rate (KEAMlr) was strongly correlated with knee extension symmetry angle and moderately with knee flexion symmetry angle. 13 A strong correlation was also found between knee flexion symmetry angle and the ground reaction force-loading rate of the intact limb. 13 Lloyd et al found strength asymmetries and determined they contributed to OA through asymmetrical loading rates taxing the intact limb.  13

Sadeghi et al have discussed the intact limb’s role in gait compensations. 16 They determined that amputees ambulate with significantly higher power bursts of the hip musculature on the intact limb at midstance and push-off. 16 An increase in hip extensor activity was also seen at heel contact of the intact limb. Sadeghi et al explained this as a compensation for the absence of ankle plantarflexion and forefoot movement at push-off in that the hip extensors on the intact limb are active for trunk control and are propelling the body forward. 16 At push-off, the intact limb demonstrated increased plantarflexion activity, decreased hip flexion activity and increased knee extension activity. 16 During double support, heel contact of the intact limb occurs while the dorsiflexors and knee extensors are acting as shock absorbers during the transfer of body weight while the hip extensors are providing the force to propel the body. 16 Lloyd et al discuss this gait pattern stating, “the intact limb must produce the force necessary to propel the body over the prosthetic limb, and absorb the impact as the center of gravity falls back down...this ‘moment avoidance’ gait strategy therefore results in increased load rates and muscular demands on the intact limb, while sparing the prosthetic side limb.” 13 Protecting the prosthetic limb from large moments results in high internal and external moments in the intact limb. Lloyd et al conclude, “large strength discrepancies between sides may therefore be related to decreased function of the prosthetic side limb, asymmetrical limb loading and an increased OA risk in the intact limb.” 13

Abnormal Joint Loading

External knee adduction moments and internal knee abduction moments have been correlated with severity of OA in abnormal joint loading. 8,17 During normal ambulation, the ground reaction force is medial to the knee joint axis creating an external adduction moment. An internal abduction moment is needed to counter the external adduction moment. 8 Consequently, an increase in external adduction moment from poor prosthetic alignment or gait deviations results in an increase in internal abduction moment from soft tissues, which in turn increases joint compression of the intact limb. 8 Norvel et al state, “the gait abnormalities exhibited by amputees with a prosthesis may result in abnormal joint loading that, over time, may lead to joint pain and degeneration” in the intact limb. 9

Royer et al examined hip and knee frontal plane moments in amputees. 17 These variables have been correlated with OA severity. 17,18 A significant difference between the peak internal abduction moment of the intact limb and prosthetic limb was present for both the hip and knee. The intact internal knee abduction moment was 0.55 ± 0.18 N m/kg whereas the prosthetic side was 0.38 ± 0.22 N m/kg (p=0.028). 17 The intact internal hip abduction moment was 0.88 ± 0.22N m/kg on the intact limb and 0.63 ± 0.19 N m/kg on the prosthetic side (p=0.01).  17 The internal knee and hip abduction moments were 46% and 39% greater, respectively, than the prosthetic side and 17% and 6% greater, respectively, than normal values. 17 Further, the prosthetic side had 23% smaller internal knee abduction moment and 31% smaller internal hip abduction moment compared to normal values. 17 Greater moments in the intact limb compared to the prosthetic limb and normal values indicate a greater risk of joint degeneration in both the knee and hip with the knee being at a greater risk than the hip.

Residual Limb Length and Amputation Level

The length of the residual limb or amputation level may contribute to OA in the intact limb through associated gait deviations. A shorter residual limb is associated with increased pelvis and trunk excursions. 19,20 Differences in joint moments and power generation during gait are also seen between transtibial and transfemoral amputees when compared to able-bodied subjects. 21 Transtibial amputees had greater peak maximal knee extensor moments, peak maximal hip flexor moments, and greater peak knee and hip joint power generation on the intact limb compared to able-bodied subjects. 21Transfemoral amputees had greater peak dorsiflexor moments, peak knee and hip extensor moments, and peak knee power generation on the intact limb compared to able-bodied subjects.  21

Bell et al compared the gait of amputees with short residual limbs (21% to 56% of the intact limb length) to long residual limbs (57% to 77% of the intact limb length).  19Amputees in the short residual group ambulated at a slower self-selected gait speed compared to the long residual limb group, 1.22 ± 0.1 m/s and 1.37 ± 0.13 m/s, respectively (p = 0.004). 19 Amputees in the short residual group had greater forward trunk flexion of 6.7° ± 1.85° whereas the long residual limb group had 4.3°±0.99° of trunk flexion, a difference of 2.3° (p= 0.003). 19 Lateral flexion was also significantly greater in the short residual limb group, 9.8° ± 1.74° compared to 6.7° ± 1.96°, a 3.6° difference (p=0.001). 19 The short residual group ambulated with 11.8° ±2 .47° of pelvic tilt and 9.8° ± 3.36° or pelvic obliquity compared to 8.2° ± 2.14° or pelvic tilt and 6.9° ± 1.60° of pelvic obliquity in the long residual group, a difference of 3.6° for pelvic tilt and 2.9° of pelvic obliquity. 19 Baum et al also reported a significant correlation between residual limb ratio and pelvic tilt excursion (R2=0.465). 20 Bell et al suggested these differences are attributable to loss of hip stabilization, and that amputees might benefit from strength training of the hip musculature. Hip abduction of the prosthetic limb in shorter residual limbs was 9.7° ± 3.46° compared to 7.1° ± 2.64° in the long residual limb group. The results of this study indicate that decreased hip abductor muscle strength and decreased lever arm secondary to shorter residual limb length may cause gait deviations in temporospatial and kinematic outcomes.19

Nolan et al examined compensations of the intact limb with net joint moments and power output in transfemoral and transtibial amputees compared to able-bodied subjects at a gait speed of 1.2m/s ± 3%. 21 Compensations seen included increased ankle range of motion, increased knee and hip extensor moments, increased knee power output, and increased hip power absorption at weight acceptance. 21 Increased knee extensor and hip flexor moment, knee power absorption and hip power output compensations were also present at push-off. 21The transtibial amputees had significantly greater peak maximal knee extensor and hip flexor moments, and peak knee and hip power output in the intact limb compared to able-bodied counterparts. 21 The transfemoral group had significantly greater peak ankle dorsiflexion moments, peak knee and hip extensor moments, and peak power output at the knee.  21These gait deviations may contribute to articular cartilage degradation through increased demands of contact force and contact pressure.

Prosthetic Components

Prosthetic components may also contribute to OA as they may influence joint loading for the intact limb. Several investigators have examined the effects of prosthetic foot type on loading of the intact limb. 22-24 An increase in loading of the intact limb may result from decreased push-off of the prosthetic limb. Improving push-off in the prosthetic limb, conversely, may decrease forces through the intact limb during double support phase. 22 Morgenroth et al explain, “if the trailing prosthetic limb produces a reduced push-off, the leading intact limb must perform a greater share of center of mass velocity redirection, thus increasing the ground reaction loading impulse on the leading limb.” 22 This increase in load increases the external adduction moment at the knee, which correlates with joint degeneration. 22 Morgenroth et al compared three different prosthetic feet with varying amounts of push-off to determine the effects of push-off on the intact limb. The prosthetic feet tested were a controlled energy storage and return foot (CESR), a conventional foot (Seattle LightFoot2), and a third foot prescribed to the subject (dynamic elastic response). 22 The research group reported a statistically significant negative relationship between push-off of the prosthetic limb and initial peak knee external adduction moment of the intact limb, indicating an increase in prosthetic push-off decreases the external adduction moment in the intact knee. 22 The CESR foot provided 68% greater push-off compared to the prescribed foot and 137% compared to the conventional foot. 22 The initial external adduction peak was significantly less in the CESR and prescribed feet compared to the conventional feet. 22

 Grabowski et al examined ambulation at different speeds with a passive-elastic foot and a powered ankle-foot compared to able-bodied counterparts. Results show the powered ankle-foot, when compared to the passive-elastic foot, decreased the peak resultant forces through the intact limb for slow to moderate gait speeds. 23 The ground reaction forces in the intact limb were also significantly less with the powered ankle-foot for gait speeds 0.75-1.50 m/s, with 6.6% lower impact peak ground reaction forces. 23 The external knee adduction moment was significantly less with the powered ankle-foot prosthesis compared to the passive-elastic prosthesis for gait speeds of 1.50 m/s and 1.75 m/s. 23 The passive-elastic foot produced greater peak resultant forces compared to able-bodied subjects. 23 Peak resultant forces of the powered ankle-foot prostheses were not significantly different than the able-bodied subjects indicating more normal gait. 23

Hill et al reported similar results when comparing passive ankle-foot prostheses to powered ankle-foot prostheses (BioM) at a gait speed of 1.25 m/s in a case series. 24 A decrease of 8% in the peak resultant force (PRF), an 18% decrease in force loading rate (FLR), an 8% decrease in peak heel-strike foot pressure (PP), and a 15% decrease in the initial peak knee external adduction moment (EAM) was present with the powered ankle-foot compared to the conventional foot. 24 A 49% decrease in lead leg transition work from step to step and a 334% increase in trailing leg transition work from step to step was present in the powered ankle-foot prosthesis compared to the passive foot. 24 These studies indicate the prosthetic foot prescription plays an important role in the loading of the intact limb and should be considered when prescribing prosthetic components as a preventative measure to OA in the intact limb.

Bone Mineral Density

Bone remodels based on the load or lack there of that is placed on it. Bone increases in density with an increase in load and decreases in density with a decrease in load. 25 Royer et al reported, “increased bone mineral density may be associated with increased risk of OA as a decrease in bone compliance places excessive wear stress on articular cartilage.” 17 Healthy individuals with greater internal knee abduction moments present with greater bone mineral density in the proximal tibia.25 Royer et al examined bone mineral density in amputees’ intact and prosthetic limb compared to controls. 25 The intact limb of amputees had 45% and 10% greater bone mineral density in the medial knee than the prosthetic limb and control, respectively. 25 The bone mineral density of the femoral neck was 12% greater in the intact limb compared to the prosthetic limb but was no different than the controls. 25 Results from both studies indicate the hip and knee of the intact limb experience increased loading and increased bone mineral density. 17,25 The hardening of subchondral bone, making it a poor absorber, coupled with joint loading further exacerbates articular cartilage degeneration. 13

**Implications of OA for Amputees**

The implications of OA for amputees are substantial. Joint pain and decreased mobility secondary to articular cartilage breakdown can result in long-term disability. 5 Functional impairment and decreased independence occur in older adults with knee OA being a leading cause of morbidity. 8 This is even more drastic when compounded with a previous disability, such as an amputation. Morgenroth et al stated, “many individuals with a lower extremity amputation face mobility challenges at baseline … OA in the joints of the intact limb can have an additive debilitating effect on mobility and quality of life in this population.” 8 Pain in the intact limb from OA can negatively impact mobility and consequently participation in vocational, educational, or social activities as OA in the intact limb is negatively correlated with prosthetic use. 26 Norvell et al reported, “a greater proportion of amputees than nonamputees reported that their pain kept them from their usual activities for more than 30 days.” 27 This decrease in participation may, in turn, negatively affect quality of life of amputees. Amputees with comorbidities are more likely to be less mobile, resulting in decreased independence with ADLs; which is a strong predictor for quality of life. 26 Geertzen et al reported comorbidities, like OA, result in a significant decrease in the Reintegration to Normal Life (RNL) score. 26 Maintaining the integrity and joint health of amputees’ intact limb is crucial in preventing further disability or setbacks.

Preventative measures should be taken to reduce the risk of OA in amputees immediately following amputation to preserve long-term function. Correcting temporal asymmetries, muscle strength asymmetries, and decreasing joint loading through prosthetic adjustment, gait training, and strength training will allow for a more symmetrical gait and more symmetrical joint loading. Addressing the factors that contribute to the development of OA will reduce the stresses felt in the hip and knee and thus prevent articular cartilage degeneration in the intact limb.

**Prevention and Intervention**

Mechanical Prevention and Intervention

Much like the mechanical treatments in the general population for OA, such as valgus bracing and lateral wedges, mechanical modifications can be made to the prosthesis to improve joint loading during gait. 8 Proper socket fit and prosthetic alignment may decrease abnormal loading of the intact limb by altering the external adduction moment and thus decreasing the internal abduction moment. 3,8 Morgenroth et al reported, “increased trailing limb push-off and feet that are functionally arc shaped during gait with larger radius of curvature are associated with reduced leading-limb loading.” 8 The type of foot component on the prosthesis may also alter the moments in the intact limb. Amputees who ambulate with an energy storage and return foot have a 13% reduction in external adduction moment in the intact limb compared to a traditional foot. 8 Significantly increasing the foot-ankle push-off of a prosthetic foot results in a 26% reduction of the initial peak external adduction moment in the intact limb. 8 Morgenroth et al stated, “prosthetic feet with optimized roll-over shape…also have the potential to decrease intact limb loading.” 8

Gait Training

After amputation, decreased body weight, change in center of mass over the base of support, altered weight acceptance, altered single limb support time, and altered limb advancement all contribute to gait asymmetries. 28 Amputees have decreased stance time on the prosthetic limb, thereby increasing the load through the intact limb with reciprocal gait. Gait training in physical therapy to correct gait deviations and temporal asymmetries may aid in preventing articular cartilage degeneration in the intact limb. Dignwell et al confirmed that amputees have significantly greater asymmetries than healthy subjects, specifically in percent stance time, push-off force, and single support time. 11 After real time visual feedback was provided, amputees significantly decreased the amount of asymmetries initially present. 11 Results indicate amputees can correct their gait mechanics with feedback to a more symmetrical gait pattern and consequently decrease abnormal joint loading of the intact limb.

Other physical therapy interventions to correct gait mechanics include proprioceptive neuromuscular facilitation (PNF). Yiğiter et al examined the effectiveness of traditional prosthetic training and PNF resistive gait training in amputees in improving weight bearing and gait. 28 One group received traditional treatment including weight shifting, balance activities, stool stepping, and gait activities while the other group received the same activities with PNF. 28 Yiğiter et al reportd, “although the outcome of this study suggested that both therapeutic approaches were effective on weight bearing and gait biomechanics, better results were attained in the group who received proprioceptive feedback.” 28 Both the Dingwell et al and Yiğiter et al studies indicate some form of feedback in gait training is beneficial in improving gait mechanics in amputees.

Strength Training

Addressing strength asymmetries will also improve joint loading during reciprocal gait. Amputees with preserved muscle strength demonstrate improved gait as a result of more control of the prosthesis and decreased energy expenditure. 29 Knee extensor, knee flexor, and hip abductor strength and symmetry correspond to improved function and symmetrical gait for amputees and should be targeted in rehabilitation. 13,30 Nadollek et al reported a number of improvements were correlated with hip abductor strength including increased weight bearing on the prosthetic limb, improved gait parameters, and decreased medio-lateral center of pressure excursion on the prosthetic side. 14 Decreased weight bearing on the prosthetic limb is correlated with weak hip abductor strength, indicating the need for adequate strength in the gluteus medius and gluteus minimus. 14 Boyd et al examined the relationship between tempro-spatial gait parameters and isometric strength and reported “results indicate that adequate force is necessary in both residual and sound limbs to improve functional gait ability.” 30 A strength-training program targeting both strength and symmetry of strength between the prosthetic and intact limbs should be implemented early on to prevent asymmetrical gait leading to OA.

Other Interventions

Other preventative strategies include weight management, activity modification in vocational and recreational settings, and knee trauma prevention. A reduction in weight can significantly reduce the risk of OA by 50%. 5 Activity modification, such as altering activities requiring knee bending or carrying objects, reduces OA rates by 15-30%. 5 Pharmacology may also be indicated in some patients but should be done so with caution. Morgenroth et al state, “analgesic medications can increase the peak knee EAM [external adduction moment] secondary to pain reduction and can potentially accelerate OA progression in the long run.” 8 This indicates a treatment that addresses mechanical factors should be considered first in rehabilitation.

 While total joint replacements in amputee patients remain rare they should not be ruled out in severe instances. When conservative treatments have been exhausted with no pain relief and continued deterioration in mobility, function, and independence, total joint replacements may be considered despite the added challenges that come with rehabilitation in amputees. In a case report, one patient received a total knee replacement for grade 4 OA in the intact limb following a below knee amputation 7 years earlier. 31 The patient received physical therapy post-operatively without limitations related to his amputation;at 6 weeks, the patient presented with improved function and was able to ambulate without assistive devices. 31 In another case report, a patient received a total hip replacement on the intact limb after having a hindquarter amputation and remained independent at follow up four years post-operatively. 32 Both cases indicate joint replacements can be preformed on amputee patients both safely and effectively when conservative treatments fail.

**Conclusion**

 With the growing number of amputations and the increased prevalence of OA in amputees, understanding the contributors and ways to prevent the development of articular cartilage degeneration in a population already facing mobility challenges is critical. Amputees ambulate with an asymmetrical gait creating an increase in joint loading on the intact limb, which results in bone remodeling and articular cartilage degeneration. Addressing temporal asymmetries through gait training with feedback, ensuring patients have proper prosthetic fit, alignment, and optimal prosthetic components, as well as providing strength training targeting hip abductors, knee flexors, and knee extensors all work to decrease the load through the intact limb. Each of these should be addressed early for their preventative benefits to ensure optimal long-term mobility, participation, and quality of life.

References:

 1. Amputee statistics. Statistics Brain Web site. [http://www.statisticbrain.com/amputee-statistics/](http://www.statisticbrain.com/amputee-statistics/%22%20%5Ct%20%22_blank). Published July 28, 2013. Updated 2013. Accessed Sept 16, 2013.

2. Limb loss resource center: Limb loss statistics. Amputee Coalition Web site. [http://www.amputee-coalition.org/limb-loss-resource-center/limb-loss-statistics/index.html](http://www.amputee-coalition.org/limb-loss-resource-center/limb-loss-statistics/index.html%22%20%5Ct%20%22_blank). Updated 2013. Accessed Sept 16, 2013.

3. Gailey R, Allen K, Castles J, Kucharik J, Roeder M. Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use. *Journal of Rehabilitation Research & Development*. 2008;45(1):15-29. [https://auth.lib.unc.edu/ezproxy\_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=31638470&site=ehost-live&scope=site](https://auth.lib.unc.edu/ezproxy_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=31638470&site=ehost-live&scope=site" \t "_blank).

4. Vincent KR, Conrad BP, Fregly BJ, Vincent HK. The pathophysiology of osteoarthritis: A mechanical perspective on the knee joint. *PM&R*. 2012;4(5, Supplement):S3-S9. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.pmrj.2012.01.020](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.pmrj.2012.01.020%22%20%5Ct%20%22_blank).

5. Struyf P. The prevalence of osteoarthritis of the intact hip and knee among traumatic leg amputees. *Arch Phys Med Rehabil*. 2009;90(3):440.

6. Burke M. Bone and joint changes in lower limb amputees. *Ann Rheum Dis*. 1978;37(3):252.

7. Kulkarni J, Adams J, Thomas E, Silman A. Association between amputation, arthritis and osteopenia in british male war veterans with major lower limb amputations. *Clin Rehabil*. 1998;12(4):348-353. [https://auth.lib.unc.edu/ezproxy\_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=5855196&site=ehost-live&scope=site](https://auth.lib.unc.edu/ezproxy_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=5855196&site=ehost-live&scope=site" \t "_blank).

8. Morgenroth DC, Gellhorn AC, Suri P. Osteoarthritis in the disabled population: A mechanical perspective. *PM&R*. 2012;4(5, Supplement):S20-S27. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.pmrj.2012.01.003](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.pmrj.2012.01.003%22%20%5Ct%20%22_blank).

9. Norvell DC, Czerniecki JM, Reiber GE, Maynard C, Pecoraro JA, Weiss NS. The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic amputees and nonamputees. *Arch Phys Med Rehabil*. 2005;86(3):487-493. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.apmr.2004.04.034](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.apmr.2004.04.034%22%20%5Ct%20%22_blank).

10. Sanderson DJ, Martin PE. Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking. *Gait Posture*. 1997;6(2):126-136. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/S0966-6362(97)01112-0](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/S0966-6362%2897%2901112-0%22%20%5Ct%20%22_blank).

11. Dingwell J. Use of an instrumented treadmill for real-time gait symmetry evaluation and feedback in normal and trans-tibial amputee subjects. *Prosthet Orthot Int*. 1996;20(2):101.

12. Kovac I, Medved V, Ostojic L. Spatial, temporal and kinematic characteristics of traumatic transtibial amputees' gait. *Coll Antropol*. 2010;34 Suppl 1:205-213.

13. Lloyd CH, Stanhope SJ, Davis IS, Royer TD. Strength asymmetry and osteoarthritis risk factors in unilateral trans-tibial, amputee gait. *Gait Posture*. 2010;32(3):296-300. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2010.05.003](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2010.05.003%22%20%5Ct%20%22_blank).

14. Nadollek H, Brauer S, Isles R. Outcomes after trans-tibial amputation: The relationship between quiet stance ability, strength of hip abductor muscles and gait. *Physiotherapy Research International*. 2002;7(4):203. [https://auth.lib.unc.edu/ezproxy\_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=8551577&site=ehost-live&scope=site](https://auth.lib.unc.edu/ezproxy_auth.php?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=8551577&site=ehost-live&scope=site" \t "_blank).

15. Isakov E, Burger H, Gregoric M, Marincek C. Stump length as related to atrophy and strength of the thigh muscles in trans-tibial amputees. *Prosthet Orthot Int*. 1996;20(2):96-100.

16. Sadeghi H. Muscle power compensatory mechanisms in below-knee amputee gait. *American journal of physical medicine & rehabilitation*. 2001;80(1):25.

17. Royer TD, Wasilewski CA. Hip and knee frontal plane moments in persons with unilateral, trans-tibial amputation. *Gait Posture*. 2006;23(3):303-306. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2005.04.003](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2005.04.003%22%20%5Ct%20%22_blank).

18. Sharma L. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheum*. 1998;41(7):1233; 1233-1240; 1240.

19. Bell JC. Transfemoral amputations: The effect of residual limb length and orientation on gait analysis outcome measures. *Journal of bone and joint surgery.American volume*. 2013;95(5):408.

20. Baum BS, Schnall BL, Tis JE, Lipton JS. Correlation of residual limb length and gait parameters in amputees. *Injury*. 2008;39(7):728-733. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.injury.2007.11.021](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.injury.2007.11.021%22%20%5Ct%20%22_blank).

21. Nolan L, Lees A. The functional demands on the intact limb during walking for active trans-femoral and trans-tibial amputees. *Prosthet Orthot Int*. 2000;24(2):117-125.

22. Morgenroth DC, Segal AD, Zelik KE, et al. The effect of prosthetic foot push-off on mechanical loading associated with knee osteoarthritis in lower extremity amputees. *Gait Posture*. 2011;34(4):502-507. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2011.07.001](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.gaitpost.2011.07.001%22%20%5Ct%20%22_blank).

23. Grabowski AM, D'Andrea S. Effects of a powered ankle-foot prosthesis on kinetic loading of the unaffected leg during level-ground walking. *J Neuroeng Rehabil*. 2013;10:49-0003-10-49. doi: 10.1186/1743-0003-10-49; 10.1186/1743-0003-10-49.

24. Hill D, Herr H. Effects of a powered ankle-foot prosthesis on kinetic loading of the contralateral limb: A case series. *IEEE Int Conf Rehabil Robot*. 2013;2013:1-6. doi: 10.1109/ICORR.2013.6650375; 10.1109/ICORR.2013.6650375.

25. Royer T, Koenig M. Joint loading and bone mineral density in persons with unilateral, trans-tibial amputation. *Clin Biomech*. 2005;20(10):1119-1125. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.clinbiomech.2005.07.003](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.clinbiomech.2005.07.003%22%20%5Ct%20%22_blank).

26. Geertzen JHB. Lower limb amputation part 2: Rehabilitation ‐ a 10 year literature review. *Prosthet Orthot Int*. 2001;25(1):14; 14-20; 20.

27. Norvell DC, Czerniecki JM, Reiber GE, Maynard C, Pecoraro JA, Weiss NS. The prevalence of knee pain and symptomatic knee osteoarthritis among veteran traumatic amputees and nonamputees. *Arch Phys Med Rehabil*. 2005;86(3):487-493. doi: [http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.apmr.2004.04.034](http://dx.doi.org.libproxy.lib.unc.edu/10.1016/j.apmr.2004.04.034%22%20%5Ct%20%22_blank).

28. Yiğiter K. A comparison of traditional prosthetic training versus proprioceptive neuromuscular facilitation resistive gait training with trans‐femoral amputees. *Prosthet Orthot Int*. 2002;26(3):213; 213-217; 217.

29. Pedrinelli A, Saito M, Coelho RF, Fontes RB, Guarniero R. Comparative study of the strength of the flexor and extensor muscles of the knee through isokinetic evaluation in normal subjects and patients subjected to trans-tibial amputation. *Prosthet Orthot Int*. 2002;26(3):195-205.

30. Boyd L. The influence of lower-extremity muscle force on gait characteristics in individuals with below-knee amputations secondary to vascular disease. *Phys Ther*. 1996;76(4):369.

31. Karam MD, Willey M, Shurr DG. Total knee replacement in patients with below-knee amputation. *Iowa Orthop J*. 2010;30:150-152.

32. Sommerville SM, Patton JT, Luscombe JC, Grimer RJ. Contralateral total hip arthroplasty after hindquarter amputation. *Sarcoma*. 2006;2006:28141. doi: 10.1155/SRCM/2006/28141.