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Factors related to high-level mobility in male servicemembers with traumatic lower-limb loss

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Abstract—The purpose of this study was to examine the possible relationship between factors modifiable by rehabilitation interventions (rehabilitation factors), other factors related to lower-limb loss (other factors), and high-level mobility as measured by the Comprehensive High-Level Activity Mobility Predictor (CHAMP) in servicemembers (SMs) with traumatic lower-limb loss. One-hundred eighteen male SMs with either unilateral transtibial amputation (TTA), unilateral transfemoral amputation (TFA), or bilateral lower-limb amputation (BLLA) participated. Stepwise regression analysis was used to develop separate regression models of factors predicting CHAMP score. Regression models containing both rehabilitation factors and other factors explained 81% (TTA), 36% (TFA), and 91% (BLLA) of the variance in CHAMP score. Rehabilitation factors such as lower-limb strength and dynamic balance were found to be significantly related to CHAMP score and can be enhanced with the appropriate intervention. Further, the findings support the importance of salvaging the knee joint and its effect on high-level mobility capabilities. Lastly, the J-shaped energy storage and return feet were found to improve high-level mobility for SMs with TTA. These results could help guide rehabilitation and aid in developing appropriate interventions to assist in maximizing high-level mobility capabilities for SMs with traumatic lower-limb loss.

Key words: CHAMP, gait, high-level mobility, injury severity, lower-limb loss, prosthetics, rehabilitation, servicemembers, traumatic amputation, waist circumference.

INTRODUCTION

Currently, many servicemembers (SMs) who experience traumatic lower-limb loss (LLL) seek return to

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Abbreviations: AIS = Abbreviated Injury Scale, AMPPro = Amputee Mobility Predictor with Prosthesis, BAMC = Brooke Army Medical Center, BLLA = bilateral lower-limb amputation, BTFA = bilateral transfemoral amputation, BTTA = bilateral transtibial amputation, CHAMP = Comprehensive High-Level Activity Mobility Predictor, CoM = center of mass, ESAR = energy storage and return, ESST = Edgren Side Step Test, HUC = Human Use Committee, IAT = Illinois Agility Test, IRB = Institutional Review Board, LLL = lower-limb loss, MPK = microprocessor knee unit, NFS = Not Further Specified, NISS = New Injury Severity Score, NMPK = nonmicroprocessor knee unit, SAT = shock absorbers and/or torque rotators, SLS = Single Limb Stance, SM = servicemember, TFA = unilateral transfemoral amputation, TTA = unilateral transtibial amputation, TTA/TFA = combination of transtibial and transfemoral amputation, VA = Department of Veterans Affairs, Womack = Womack Army Medical Center, WRAMC = Walter Reed Army Medical Center.

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Active Duty and return to high-level mobility activities such as sports. Between 2001 and 2009, it is estimated that between 11 to 16 percent of SMs with traumatic LLL at various levels of amputation returned to duty [1–2]. Of SMs with unilateral and multiple LLL, 26 percent from Operation Enduring Freedom and 19 percent from Operation Iraqi Freedom returned to high-level activities such as basketball and skiing [3]. Because many SMs seek return to high-level mobility but not all achieve it, it is important for both the SMs and clinicians involved in their rehabilitation to understand those factors modifiable by rehabilitation interventions (rehabilitation factors) as well as other factors related to LLL that are associated with achieving this goal. Unfortunately, many of these factors are not well understood, in part because, until recently, there was no way to measure high-level mobility at various stages in the rehabilitation process for this population.

The Comprehensive High-Level Activity Mobility Predictor (CHAMP) was created to quantify the ability of SMs with limb loss to perform high-level mobility activities. The CHAMP assesses balance, postural stability, coordination, power, speed, and agility in multiple planes of motion and has been demonstrated to be a reliable and valid measure of high-level mobility in SMs with limb loss [4–5]. By using the CHAMP to measure high-level mobility, it may be possible to identify factors that are related to ability to perform high-level mobility activities. This type of information could help guide clinicians in setting rehabilitation goals and developing clinical interventions for SMs with traumatic LLL who want to return to high-level activity.

There are a number of factors that potentially can be modified during the rehabilitation intervention that may be related to return to high-level mobility. Rehabilitation factors include muscle strength and power [6–7], range of motion, balance strategies and proprioceptive control [8–11], and gait pattern [10,12–14]. Other factors include weight [15] and adiposity as reflected by waist circumference, age, time since amputation, number and level of amputations as reflected in the number of remaining intact knee and ankle joints [7,16–18], and condition of the amputated and contralateral lower limb (if applicable), as well as length of the residual limb [19–22]. In addition, prosthetic feet [23–27] and knee units have been shown to affect basic prosthetic mobility and may also affect high-level mobility [12].

The purpose of this study was to examine the possible relationship between rehabilitation factors, other factors, and high-level mobility as measured by the CHAMP in SMs with traumatic LLL. We hypothesized that rehabilitation factors such as strength, balance, and gait components represented by individual test items of the Amputee Mobility Predictor with Prosthesis (AMPPro), and other factors such as weight, waist circumference, age, time since amputation, level of amputation, number of limbs lost, severity of musculoskeletal injury, residual-limb length, prosthetic ankle/foot design, and prosthetic knee device would be related to high-level mobility, as measured by participants' CHAMP scores (**Tables 1** and **2**).

METHODS

Study Design

This was a cross-sectional, correlative-predictive study. Data were collected at Walter Reed Army Medical Center (WRAMC), Washington, DC; Center for the Intrepid, Brooke Army Medical Center (BAMC), San Antonio, Texas; and Womack Army Medical Center (Womack), Fort Bragg, North Carolina.

Participants

A convenience sample of 118 Active Duty or retired male SMs between the ages of 18 and 40 yr with traumatic LLL completed the study. Participants who were medically stable with a properly fitting prosthesis and demonstrated a minimal level of function, as determined by ability to walk at least 250 m in the 6-Minute Walk Test, completed the study. Participants were excluded if they had spinal cord injury; upper-limb loss; peripheral nerve injury that limited function; orthopedic, cardiopulmonary, or contralateral limb injuries that limited mobility or exercise; or inability to follow commands or physical limitations because of traumatic brain injury. The participants had LLLs at a variety of levels: unilateral transtibial amputation (TTA); unilateral transfemoral amputation (TFA); and bilateral lower-limb amputation (BLLA), including bilateral transtibial amputation (BTTA), bilateral transfemoral amputation (BTFA), and a combination of transtibial and transfemoral amputation (TTA/TFA).

Study Procedures

Two physical therapists who were currently working or had previously worked in the Armed Forces Amputee

Patient Care Program Rehabilitation Centers at WRAMC and BAMC interviewed all participants for this study. Information such as demographic characteristics; prosthetic components currently being used for each participant's prosthesis; and anthropometric measurements such as height, body mass, and waist circumference were collected for all participants. All participants completed a self-report inventory of musculoskeletal injuries caused by the traumatic event.

High-Level Mobility

High-level mobility was measured using the CHAMP. The CHAMP is composed of four tests: Single Limb Stance (SLS), Edgren Side Step Test (ESST), T-Test, and Illinois Agility Test (IAT) [4,28–34]. Testing was administered outdoors on either a smooth surface under a covered patio or indoors in a gymnasium on a hardwood floor. Teams of two investigators observed the participants. Each participant performed the CHAMP independently to avoid competition. A rest period of up to 2 min between each CHAMP item was required. Participants were asked to perform each test twice, with the best score of the two trials selected for data analysis. In the event a participant was unable to successfully complete a test in two trials because of a disqualification or a fall, a third trial was permitted. To maintain consistency, we determined prior to testing to use the data from one tester for analysis of CHAMP performance. The best times/points reported by the selected tester for each individual CHAMP item (SLS, ESST, T-Test, and IAT) were converted to a 0 to 10 scoring system, with higher scores indicating better performance. The scores for each individual test were added together to produce a composite CHAMP score with a 0 to 40 scoring range. Higher scores indicate better performance on the CHAMP [4].

Rehabilitation-Related Factors

The AMPPro is a 20-item, performance-based instrument designed to evaluate component skills required to ambulate with a prostheses [35]. Individual AMPPro items are similar to the items on many performance-based measures of strength, balance, and gait [36–38], and previous research has demonstrated that individual AMPPro items can be used as surrogate measures of lower-limb strength, balance, and gait components [7]. The AMPPro was administered indoors on a flat surface by the same physical therapist at all testing sites. **Table 1** describes the AMPPro items used to represent various constructs. The AMPPro items are scored as 0 = unable to perform the task, 1 = requires assistance or modification to perform task, and 2 = performs task independently without modification.

Other Lower-Limb Loss Factors

Weight and Waist Circumference

Height was measured in centimeters in a standing position, from the crown of the participant's head to the floor using a static tape measure. Participants wore their prosthesis when weighed to the nearest kilogram while standing on a calibrated portable scale. Waist circumference was determined using a standard tape measure to the nearest centimeter at the midpoint between the lowest rib and the iliac crest (**Table 2**) [39–40].

Age and Time Since Amputation

Age and time since amputation were based on participant self-report (**Table 2**). Age at time of testing was calculated by subtracting the participant's date of birth from the date of testing. Time since amputation was determined by subtracting the participant's date of traumatic event from the date of testing.

Level of Amputation and Number of Remaining Lower-Limb Joints

The participants were grouped according to level of amputation into TTA, TFA, and BLLA groups. The BLLA group included participants with BTTA, BTFA, and TTA/TFA. Participants with knee disarticulation were placed in the TFA group. Participants were also placed into one of four groups based on their combined number of remaining ankle and knee joints: three joints (one ankle and two knee joints) included subjects with TTA, two joints (either one ankle and one knee joint or two knee joints) included subjects with either TFA or BTTA, one joint (one knee joint) included subjects with TTA/TFA, and no joints (no knee or ankle joints) included subjects with BTFA.

Musculoskeletal Injury Severity

Each participant's injuries were categorized into anatomical body regions using the self-report Abbreviated Injury Scale (AIS) [41]. The AIS classifies injuries as (1) minor, (2) moderate, (3) serious, (4) severe, (5) critical, or (6) maximal/currently untreatable. Conservative coding, which is assigning the least severe AIS code or the Not Further Specified (NFS) severity code, was used to assign the severity code to each injury. The New Injury Severity

Table 1.
Rehabilitation candidate factors related to high-level mobility, as measured by Comprehensive High-Level Activity Mobility Predictor, in servicemembers with traumatic lower-limb loss.

Construct	Measure	Description
Lower-Limb Strength and Dynamic Balance	AMPPro Item 4: Arise from chair	Unable without help (physical assistance) = 0; Able, uses arms/AD to help = 1; Able, without using arms = 2
Lower-Limb Strength, Dynamic Balance, and Organizational Skills	AMPPro Item 5: Attempts to arise from chair	Unable without help (physical assistance) = 0; Able requires > 1 attempt = 1; Able to rise 1 attempt = 2
Standing Balance	AMPPro Item 6: Immediate standing balance	Unsteady (staggers, moves foot, sways) = 0; Steady using walking aid or other support = 1; Steady without walker or other support = 2
Standing Balance and Displacement of CoM over BoS	AMPPro Item 9: Standing reach	Does not attempt = 0; Cannot grasp or requires support = 1; Successfully grasps item no support = 2
Standing Balance and Ankle, Hip, and Step Strategy	AMPPro Item 10: Nudged	Begins to fall = 0; Staggers, grabs, catches self uses AD = 1; Steady = 2
Standing Balance (Vestibular and Proprioceptive Systems)	AMPPro Item 11: Eyes closed	Unsteady or grips AD = 0; Steady without any use of AD = 1
Dynamic Balance and Displacement of CoM over BoS	AMPPro Item 12: Picking up object off floor	Unable to pick up object and return to standing = 0; Performs with some help (walking aid) = 1; Performs independently = 2
Lower-Limb Strength and Dynamic Balance	AMPPro Item 13: Sitting down	Unsafe (misjudged distance, falls into chair) = 0; Uses arms, AD, not a smooth motion = 1; Safe, smooth motion = 2
Gait Component*	AMPPro Item 15: Step length and height	Does not advance minimum of 12 inches = 0; Advances minimum of 12 inches = 1; Foot does not completely clear floor = 0; Foot completely clears floor = 1
Dynamic Balance	AMPPro Item 17: Turning	Unable to turn = 0; Greater than 3 steps but completes task = 1; No more than 3 steps with or without AD = 2
Gait Component	AMPPro Item 18: Variable cadence	Unable to vary cadence in controlled manner = 0; Asymmetrical increase in cadence = 1; Symmetrical increase in speed = 2
Dynamic Balance and Prosthetic Control	AMPPro Item 19: Stepping over obstacle	Cannot step over box = 0; Catches foot, interrupts stride = 1; Steps over without interrupting stride = 2
Lower-Limb Strength and Dynamic Balance†	AMPPro Item 20a: Ascending stairs	Unsteady, cannot do = 0; One step at a time, or holds on to railing = 1; Step over step, does not hold onto railing = 2
Lower-Limb Strength and Dynamic Balance†	AMPPro Item 20b: Descending stairs	Unsteady, cannot do = 0; One step at a time, or holds on to railing = 1; Step over step, does not hold onto railing = 2

*Scores given for both lower limbs.
†Scores given for ascending and descending stairs.
AD = assistive device, AMPPro= Amputee Mobility Predictor with Prosthesis, BoS = base of support, CoM = center of mass.

Score (NISS), which is the sum of the squares of the three most severe injuries, was calculated to determine each participant's injury severity score while controlling for level of amputation. The NISS ranges from 1 to 75, with higher scores indicating greater severity of injury [42].

Residual-Limb Length

The residual-limb length for those with TTA was measured from the knee joint line to the end of the soft tissue, and those with TFA were measured from the greater trochanter to the end of the soft tissue. This measure was only included in the regression models for participants with unilateral LLL.

Prosthetic Components

The prosthetic ankle/foot assemblies were divided into three categories: J-shaped energy storage and return (ESAR) feet with shock absorbers and/or torque rotators

Table 2.
Other lower-limb loss candidate factors related to high-level mobility, as measured by Comprehensive High-Level Activity Mobility Predictor, in servicemembers with traumatic lower-limb loss.

Construct	Measure	Description
Body Height	Crown of Head to Floor	Measured in centimeters.
Body Weight	Health-o-Meter	Measured in kilograms.
Central Adiposity	Waist Circumference	Measured in centimeters.
Age	Date of Birth	Years and months measured from testing session 1 to date of birth.
Time Since Amputation	Date of Amputation	Years and months measured from testing session 1 to date of traumatic event.
Lower-Limb Amputation Level	Unilateral or Bilateral	TTA = 1, TFA = 0, BLLA = –1.
Bilateral Amputation Level	Remaining Intact Knee Joints	BTTA = 2, TTA/TFA = 1, BTFA = 0.
Lower-Limb Joint Salvage Following Amputation	Remaining Knee and Ankle Joints	TTA (2 knee joints and 1 ankle joint) = 3, TFA (1 knee joint and 1 ankle joint) = 2, BTTA (2 knee joints) = 2, TTA/TFA (1 knee joint) = 1, BTFA (0 knee joints) = 0.
Musculoskeletal Injury Severity	New Injury Severity Score	1–75 scoring system; Higher scores = greater injury severity.
Residual Limb Length*	Length of Remaining Tibia or Femur	Measured in centimeters.
Prosthetic Ankle Foot Assembly	Type of ESAR Foot	J-Shaped ESAR Foot with SA and/or TR = 1, J-Shaped ESAR Foot = 0, Low-Profile ESAR Foot = –1.
Prosthetic Knee Unit	Type of Prosthetic Knee Unit	Microprocessor controlled knee unit = 1, Nonmicroprocessor controlled knee unit = 0.

*Used only for those with unilateral lower-limb loss.
BLLA = bilateral lower-limb amputation, BTFA = bilateral transfemoral amputation, BTTA = bilateral transtibial amputation, ESAR = energy storage and return, TFA = unilateral transfemoral amputation, TTA = unilateral transtibial amputation, TTA/TFA = combination of transtibial and transfemoral amputation, SA = shock absorber, TR = torque rotator.

(SAT) (J-shaped SAT), J-shaped ESAR feet (J-shaped), and low profile ESAR feet (low profile) [23–24]. The types of J-shaped SAT feet worn were the Össur Re-Flex VSP (Reykjavík, Iceland), Össur Ceterus, Ohio Willow Wood Pathfinder II (Mt. Sterling, Ohio), and Freedom Innovation Renegade (Irvine, California). The types of J-shaped feet worn were Össur Talux, Össur Modular III, Össur Vari-flex, and Ottobock Springlite II (Duderstadt, Germany). The type of low-profile feet worn were Össur LP Vari-flex, Ottobock C-Walk, Ottobock 1E56 Axtion, and Endolite Echelon (Sheffield, United Kingdom).

The prosthetic knee units were divided into two categories: microprocessor and nonmicroprocessor knee units [23]. The types of microprocessor knee units worn were Ottobock C-Leg, Ottobock Genium X2, Össur Rheo Knee, and Freedom Innovation Plié 2.0. The types of nonmicroprocessor knee units worn were Össur Total Knee 1900, Endolite Mercury Knee, Ottobock 3R80 Knee, and Össur Mauch SNS Knee.

Statistical Analysis

Statistical analyses were performed using SAS version 9.13 (SAS Institute Inc; Cary, North Carolina). Descriptive statistics were used to characterize the sample. We initially examined the relationship between levels of amputation (TTA vs TFA vs BLLA), number of remaining knee and ankle joints, and CHAMP score. Spearman correlation coefficients confirmed a strong positive correlation between level of amputation and CHAMP score ($r = 0.75$, $p < 0.001$), indicating that participants with unilateral distal amputation had higher CHAMP scores and thus greater high-level mobility than those with unilateral proximal amputation and bilateral amputation. A strong positive correlation was also found between the number of remaining knee and ankle joints and CHAMP score ($r = 0.78$, $p < 0.001$), indicating that having more intact lower-limb joints was associated with higher CHAMP scores. Because both level of amputation and the number of intact knee and ankle joints were so strongly related to high-level mobility, we constructed separate regression models for each of the primary amputation levels (TTA, TFA, and BLLA). Since the BLLA group included participants with BTTA, BTFA, and TTA/TFA, we included a variable representing the number of intact knees in the regression model for the BLLA group.

Stepwise regression was used to identify which rehabilitation factors and other factors were related to high-level mobility as measured by CHAMP score. Candidate variables are represented in **Tables 1** (rehabilitation factors) and **2** (other factors). In model 1, we identified the rehabilitation factors that were related to high-level mobility as measured by CHAMP score. In model 2, we identified the other factors that were related to high-level mobility. In the final combined model, we determined which of the rehabilitation factors and other factors from models 1 and 2 were in combination most strongly related to high-level mobility. Separate models were generated for individuals with TTA, TFA, and BLLA.

RESULTS

The baseline characteristics for the different amputation groups (TTA, TFA, BLLA) are described in **Table 3**. The groups were similar in NISS, height, weight, waist circumference, age, and time since injury. There were significant differences in CHAMP score among SMs with TTA, TFA, and BLLA.

The results of the separate regression analyses for TTA, TFA, and BLLA are presented in subsequent paragraphs, followed by findings from an analysis of the contribution of prosthetic components.

Stepwise Regression Model for Servicemembers with Transtibial Amputation

Table 4 describes the stepwise regression analysis for SMs with TTA. The final combined model accounted for 81 percent of variance in high-level mobility as measured by CHAMP score. The majority of variance in CHAMP score was attributed to the SM's ability to descend stairs (68%), followed by the ability to ascend stairs (3%), waist circumference (3%), type of prosthetic ankle/foot assembly worn (3%), and time since amputation (4%). Greater high-level mobility was related to lower-limb strength and dynamic balance, smaller waist circumference, use of a J-shaped SAT foot or J-shaped foot, and greater time spent with an amputation.

Stepwise Regression Model for Servicemembers with Transfemoral Amputation

Table 5 describes the stepwise regression analysis for those with TFA. The final combined model accounted for 36 percent of variance in high-level mobility as measured by CHAMP score. The variance in CHAMP score was attributed to waist circumference (13%), NISS (13%), and the ability to sit down from standing (10%). Greater high-level mobility was related to smaller waist circumference, less musculoskeletal injury severity, and lower-limb strength and dynamic balance.

Table 3.
Characteristics of study participants by three primary levels of amputation. All data given as mean ± standard deviation (range) unless otherwise noted.

Characteristic	TTA	TFA	BLLA
Participants (*n*)	60	32	26
NISS (points)*	4.0 (0–22)	8.5 (0–36)	7.0 (0–17)
Residual-Limb Length (cm)	16.7 ± 3.9 (8.5–29)	34.1 ± 7.6 (17–49)	—
Height (cm)	181.4 ± 7.8 (158.8–197.5)	181.5 ± 5.2 (168.9–190.5)	182.0 ± 7.7 (170.2–203.2)
Weight (kg)	90.1 ± 16.1 (56.6–133.7)	90.2 ± 12.2 (69.9–118.8)	91.0 ± 18.6 (60.8–141.1)
Waist Circumference (cm)	92.4 ± 10.1 (71.1–125.1)	95.5 ± 9.0 (72.39–114.3)	96.6 ± 10.4 (78.7–116.8)
Age (yr)	28.5 ± 5.8 (20–40)	30.6 ± 5.5 (22–40)	28.6 ± 5.5 (22–40)
Time Since Injury (yr)	3.2 ± 2.2 (0.4–11.8)	3.3 ± 1.3 (1.0–6.0)	2.8 ± 2.0 (0.5–10.4)
CHAMP Score (points)†	26.9 ± 5.6 (8–35)	19.6 ± 3.4 (13–25)	13.2 ± 7.2 (1–24.5)

*NISS reported as median value.
†Significant differences ($p < 0.05$) between all levels of amputation.
BLLA = bilateral lower-limb amputation, CHAMP = Comprehensive High-Level Activity Mobility Predictor, NISS = New Injury Security Score, TFA = unilateral transfemoral amputation, TTA = unilateral transtibial amputation.

Table 4.
Rehabilitation factors and other factors related to high-level mobility, as measured by Comprehensive High-Level Activity Mobility Predictor score, for servicemembers with unilateral transtibial amputation.

Step	Variable	Parameter Estimate	R^2	Partial R^2	Tolerance	F	p-Value
Model 1: Rehab Factors; n = 60, R^2 = 0.71, p < 0.001 (df = 59)							
1	Lower-Limb Strength and Dynamic Balance (AMPPro 20b: Descend Stairs)	6.33	0.68	—	0.62	124.86	<0.001
2	Lower-Limb Strength and Dynamic Balance (AMPPro 20a: Ascend Stairs)	13.33	0.71	0.03	0.62	5.62	0.02
Model 2: Other Factors; n = 60, R^2 = 0.49, p < 0.001, (df = 59)							
1	Prosthetic Ankle/Foot Assembly	3.42	0.18	—	0.83	12.97	<0.001
2	Central Adiposity (Waist Circumference)	–0.41	0.28	0.10	0.74	8.04	0.001
3	Time Since Amputation	0.93	0.37	0.09	0.87	8.08	0.01
4	Age	–0.30	0.47	0.10	0.76	9.31	0.003
5	Musculoskeletal Injury Severity (NISS)	–0.18	0.49	0.02	0.91	2.60	0.11
Final Combined Model; n = 60, R^2 = 0.81, p < 0.001 (df = 59)							
1	Lower-Limb Strength and Dynamic Balance (AMPPro 20b: Descend Stairs)	9.87	0.68	—	0.51	124.86	<0.001
2	Lower-Limb Strength and Dynamic Balance (AMPPro 20a: Ascend Stairs)	8.23	0.71	0.03	0.60	5.62	0.02
3	Central Adiposity (Waist Circumference)	–0.34	0.74	0.03	0.90	7.44	0.01
4	Prosthetic Ankle/Foot Assembly	2.06	0.77	0.03	0.82	7.49	0.01
5	Time Since Amputation	0.47	0.81	0.04	0.94	10.17	0.002

AMPPro = Amputee Mobility Predictor with Prosthesis, NISS = New Injury Severity Score.

Stepwise Regression Model for Servicemembers with Bilateral Lower-Limb Amputation

Table 6 describes the stepwise regression analysis for the SMs with BLLA. The final combined model accounted for 91 percent of variance in high-level mobility as measured by CHAMP score. The majority of variance in CHAMP score was attributed to the number of intact knee joints (69%), followed by ability to descend stairs (11%), ability to perform standing reach (7%), and waist circumference (4%). Greater high-level mobility was related to having at least one intact knee joint, lower-limb strength, standing and dynamic balance, ability to displace the center of mass (CoM) over the base of support, and a larger waist circumference.

Contribution of Prosthetic Components

Significant differences ($p < 0.05$) in high-level mobility as measured by CHAMP score among SMs with TTA were only found between those who wore J-shaped SAT (27.8 ± 4.1, $p < 0.05$) and low-profile feet (17.4 ± 9.5) and between the J-shaped feet (26.5 ± 6.0, $p < 0.05$) and low-profile feet. Differences ($p < 0.05$) were not found in CHAMP scores between SMs with TFA who used J-shaped ESAR feet (19.5 ± 3.4) and low-profile ESAR feet (19.9 ± 3.2) and between the microprocessor knee unit (MPK) (19.6 ± 3.5) and nonmicroprocessor knee unit (NMPK) (19.7 ± 3.0) users.

Significant differences ($p < 0.05$) were found among SMs with BLLA between those who wore J-shaped SAT feet (16.19 ± 5.90, $p < 0.05$) and low-profile feet (5.29 ± 3.79) and between the J-shaped feet (17.38 ± 6.30, $p < 0.05$) and low-profile feet. The type of prosthetic knee unit was not included as a variable for stepwise regression analysis for SMs with BLLA because not all of the participants utilized a prosthetic knee unit.

DISCUSSION

We found that both rehabilitation factors and other factors were related to high-level mobility, as measured by the CHAMP, in SMs with traumatic LLL. The level of amputation and number of intact knee and ankle joints strongly predicted CHAMP performance. This finding supports the importance of preserving the knee joint when possible to maximize the functional potential of SMs with LLL [43]. The ability to optimally utilize the

Table 5.
Rehabilitation factors and other factors related to high-level mobility, as measured by Comprehensive High-Level Activity Mobility Predictor score, for servicemembers with unilateral transfemoral amputation.

Step	Variable	Parameter Estimate	R^2	Partial R^2	Tolerance	F	p-Value
Model 1: Rehab Factors; n = 32, R^2 = 0.18, p = 0.05 (df = 31)							
1	Lower-Limb Strength and Dynamic Balance (AMPPro 13: Sit Down)	5.57	0.10	—	0.99	3.38	0.07
2	Lower-Limb Strength and Dynamic Balance (AMPPro 20a: Ascend Stairs)	3.09	0.18	0.08	0.99	2.79	0.10
Model 2:Other Factors; n = 32, R^2 = 0.25, p = 0.02 (df = 30)							
1	Central Adiposity (Waist Circumference)	–0.46	0.12	—	0.87	4.05	0.05
2	Musculoskeletal Injury Severity (NISS)	–0.16	0.25	0.13	0.87	5.03	0.03
Final Combined Model; n = 32, R^2 = 0.36, p = 0.01 (df= 31)							
1	Central Adiposity (Waist Circumference)	–0.46	0.13	—	0.86	4.69	0.03
2	Musculoskeletal Injury Severity (NISS)	–0.16	0.26	0.13	0.86	5.22	0.03
3	Lower-Limb Strength and Dynamic Balance (AMPPro 13: Sit Down)	5.60	0.36	0.10	0.99	4.02	0.05

AMPPro = Amputee Mobility Predictor with Prosthesis, NISS = New Injury Severity Score.

Table 6.
Rehabilitation factors and other factors related to high-level mobility, as measured by Comprehensive High-Level Activity Mobility Predictor score, for servicemembers with bilateral lower-limb amputation.

Step	Variable	Parameter Estimate	R^2	Partial R^2	Tolerance	F	p-Value
Model 1: Rehab Factors; n = 26, R^2 = 0.94, p < 0.001 (df = 25)							
1	Lower-Limb Strength and Dynamic Balance (AMPPro 4: Stand up)	2.72	0.66	—	0.32	46.29	<0.001
2	Balance: Dynamic (AMPPro 19: Step Over Obstacle)	2.85	0.80	0.14	0.48	17.20	<0.001
3	Lower-Limb Strength and Dynamic Balance (AMPPro 20b: Descend Stairs)	5.73	0.86	0.06	0.57	10.50	0.004
4	Balance: Dynamic and Displacement of CoM over BoS (AMPPro 12: Pick-up Object)	4.16	0.92	0.06	0.58	14.41	0.001
5	Gait Component (AMPPro 18: Vary Cadence)	2.25	0.93	0.01	0.56	4.76	0.04
6	Balance: Standing and Displacement of CoM Over BoS (AMPPro 9: Standing Reach)	2.68	0.94	0.01	0.36	3.80	0.06
Model 2: Other Factors; n = 26, R^2 = 0.80, p < 0.001 (df = 25)							
1	Number of Intact Knee Joints	5.92	0.69	—	0.79	54.46	<0.001
2	Time Since Amputation	0.92	0.76	0.07	0.94	6.82	0.01
3	Central Adiposity (Waist Circumference)	0.38	0.80	0.04	0.79	4.04	0.05
Final Combined Model; n = 26, R^2 = 0.91, p < 0.001 (df = 25)							
1	Number of Intact Knee Joints	1.52	0.69	—	0.33	54.46	<0.001
2	Lower-Limb Strength and Dynamic Balance (AMPPro 20b: Descend Stairs)	5.75	0.80	0.11	0.59	13.64	0.001
3	Balance: Standing and Displacement of CoM over BoS (AMPPro 9: Standing Reach)	3.71	0.87	0.07	0.40	11.69	0.002
4	Central Adiposity (Waist Circumference)	0.31	0.91	0.04	0.73	10.28	0.004

AMPPro = Amputee Mobility Predictor with Prosthesis, BoS = base of support, CoM = center of mass.

knee and hip musculature provides a significant biomechanical advantage when performing high-level mobility.

Stepwise Regression Model for Servicemembers with Transtibial Amputation

In the final combined model, five variables predicted 81 percent of the variance in CHAMP scores for SMs with TTA. The rehabilitation factors addressing descending and ascending stairs accounted for 71 percent of CHAMP score by themselves. Descending and ascending stairs requires prosthetic control via isometric contraction of the residual-limb musculature to stabilize the limb within the residual-limb/socket interface; dynamic single-limb balance to stabilize the head, arms, and trunk over the base of support; and sufficient lower-limb strength via eccentric and concentric contraction of the lower-limb musculature to raise and lower the body to the next step [44–45]. Impaired lower-limb muscle strength from quadriceps femoris, hamstrings, and gluteus maximus muscles, as measured by the ability to ascend and descend stairs, could affect high-level mobility performance. In order to perform maximally on the CHAMP, it is necessary to perform quick, alternating eccentric and concentric contractions of the lower-limb musculature to generate maximum power in multiple planes. A rehabilitation intervention for TTA geared toward improving speed of muscular contraction, lower-limb strength and power, and dynamic balance could lead to improved high-level mobility.

Even when combined with the rehabilitation factors, waist circumference remained a significant predictor of CHAMP performance for those with TTA. Greater waist circumference was associated with poorer performance on the CHAMP. Waist circumference is used as a measure of central adiposity [39–40] and is a predictor of cardiovascular disease in people with traumatic LLL [46]. Greater waist circumference is also associated with lower levels of physical activity and fitness [40]. To the extent that this measure is related to general fitness, it may be modifiable through a rehabilitation program designed to improve cardiovascular fitness. Improving cardiovascular fitness may improve CHAMP score.

SMs with TTA who used the J-shaped ESAR foot performed better on the CHAMP than those using other prosthetic feet even after controlling for lower-limb strength, dynamic balance, and central adiposity. The design and properties of the J-shaped ESAR foot allows for a combination of increased dynamic dorsiflexion and active knee and hip flexion, leading to greater lower-limb power production. It also has a long toe-lever that extends the length of the prosthetic foot, allowing maximum toe load and energy return from the foot that improves SLS time [23–24].

Time since amputation remained significantly associated with high-level mobility in the final combined model. It appears that the longer the time since limb loss, the better the SMs were able to perform high-level mobility activities. In SMs with traumatic LLL, it appears that more time spent with limb loss and as prosthetic ambulators provided the opportunity to maximize physical function and prosthetic use.

Stepwise Regression Model for Servicemembers with Transfemoral Amputation

In the final combined model, three variables—waist circumference, NISS, and ability to sit down from standing—predicted 36 percent of the variance in CHAMP scores for SMs with TFA. Waist circumference results for these participants were similar to those with TTA, indicating that less central adiposity was associated with greater high-level mobility. Since central adiposity is related to general fitness, this again suggests that interventions to improve general cardiovascular fitness may improve high-level mobility.

The NISS results suggest that the lower the injury severity and/or the fewer injuries to the intact and amputated lower limb, trunk, and upper limbs, the higher the CHAMP score and thus greater high-level mobility. The NISS has never been utilized in the literature to predict performance-based outcome results in people with LLL. The condition of the intact and amputated limb, trunk, and upper limbs is very important in determining the functional status of individuals with unilateral LLL. Individuals with TFA are more susceptible to postural asymmetries at the pelvis and hip and degenerative changes to the intact hip, knee, and ankle joints that may impair function and restrict activity over the long-term [47–48]. For the clinician, it is imperative to consider not only the amputated limb but also the health of the intact lower limb, trunk, and upper limbs when considering high-level mobility capabilities.

After controlling for the other factors, the ability to perform a stand-to-sit activity in a safe, smooth motion without the use of upper-limb support was the only rehabilitation factor found to be a significant predictor of CHAMP score for those with TFA. Greater lower-limb strength and dynamic balance were associated with better high-level mobility in SMs with TFA. Research examining sit-to-stand and stand-to-sit symmetry for individuals with TFA using different prosthetic knee units has demonstrated asymmetry in weight bearing between the contralateral and amputated limb, concluding that the activity is a single-limb task primarily performed with the contralateral limb [49]. Our research results support the importance of symmetrical weight distribution between the limbs and its effect on high-level mobility. If individuals with LLL do not demonstrate symmetrical weight distribution between both limbs, thus not utilizing the remaining musculature of the residual limb to perform basic and high-level mobility activities, they cannot take advantage of the potential contribution of the prosthetic knee unit and ankle/foot assembly.

The type of prosthetic knee unit and prosthetic ankle/foot assembly did not explain a significant amount of the variance in CHAMP score in SMs with TFA. No difference in CHAMP scores were seen between those who used either the MPK or NMPK. The results are consistent with previous research that found no differences in energy expenditure, oxygen consumption, and fast-walking speed between MPK and NMPK users [50–52]. Unlike the results of the participants with TTA, no differences in CHAMP score were found between J-shaped feet users and low-profile feet users among SMs with TFA. For the SMs with TFA, the type of prosthetic knee unit and ankle/foot assembly had negligible effect on CHAMP performance.

Stepwise Regression Model for Servicemembers with Bilateral Lower-Limb Amputation

In the final combined model, four variables predicted 91 percent of the variance in CHAMP scores for SMs with BLLA. A variable representing the number of remaining intact knees was made in order to analyze one model for SMs with BLLA. The number of remaining intact knees predicted 69 percent of variance in CHAMP score. The SMs with BLLA with two intact knees performed better than those with one or no intact knees, and those with one intact knee performed better than those with no intact knees. These results underline the importance of salvaging the knee joints and remaining lower-limb musculature to provide the greatest potential for high-level mobility for those with BLLA. Participants with BLLA who had bilateral knee joints that retained the original insertion sites for the quadriceps femoris and hamstring muscles had an advantage in performing high-level mobility activities. Participants with TTA/TFA and BTFA who are missing osseous structures and lower-limb musculature have limited ability to generate muscle power and maintain balance during high-level mobility.

After controlling for the number of intact knees, two rehabilitation factors, the abilities to descend stairs and to perform standing reach activity, combined to predict 18 percent of variance in CHAMP score. Both “descending stairs” and “standing reach” require displacing the CoM forward over the base of support. These activities requires prosthetic control within the residual limb-socket interface, postural extensor strength, and efficient utilization of range of motion at the hips. Trunk strength and hip flexibility play an important role in performing these activities. This assertion is supported by the findings of military colleagues who have identified the importance of trunk exercises for SMs with BLLA in order to enhance the ability to perform upper- and lower-limb functional activities [53]. Future research is needed to determine the role of trunk musculature in high-level mobility for those with BLLA.

Waist circumference remained a significant predictor of CHAMP score for SMs with BLLA. Unlike the findings for the TTA and TFA groups, in the BLLA group, greater waist circumference was associated with higher CHAMP scores. There are possible explanations for this finding. The BLLA group included both BTTA and BTFA. Although we included a variable representing the number of remaining intact knees in the regression model for BLLA, waist circumference may have remained somewhat related to level of amputation. Hoffman et al. reported that individuals with BTFA ambulated at a self-selected walking speed that was 72 percent slower and required 300 percent greater energy cost per unit distance than those without amputation [54]. The higher level of energy expenditure required for ambulation by the BTFA group, as compared with the BTTA and TTA/TFA groups, could have been associated with both less central adiposity and lower CHAMP scores.

Limitations

For SMs with TTA, 19 percent of variance in CHAMP score remained unaccounted for. Self-efficacy and self-motivation have been found to be determinants of physical activity in SMs [55]. Preamputation function has been found to be a significant predictor of postamputation function in geriatric individuals with LLL [56–57]. Future research should examine the effects of self-efficacy, self-motivation, and preamputation function and/or current physical activity as potential predictors of high-level mobility.

For SMs with TFA, 64 percent of variance in CHAMP performance remained unaccounted for. Only three variables were found to be predictors of high-level mobility for those with TFA, which was consistent with the sample size. A greater number of participants would have increased the capabilities of the regression model to account for a greater number of factors for those with TFA. Furthermore, the BLLA (BTTA, BTFA, and TTA/TFA) participants were collapsed together in order to establish comparable regression models with the other amputation levels. Future studies should examine the predictive factors of high-level mobility, using the CHAMP, among individuals with BTTA, BTFA, and TTA/TFA individually using a larger sample size.

The NISS was utilized uniquely in the study in order to determine injury severity to the upper and lower limbs and trunk of the SMs with LLL. Because of the nature of the AIS injury classification system used for the NISS, many of the injuries had to be categorized in a conservative manner (NFS) because the participants provided subjective information in terms of their injuries. For example, instead of specific details pertaining to fracture type or degree of nerve injury, which may have increased the injury severity grade, they were only able to identify the bone that was fractured and the nerve that was injured, which resulted in a conservative injury grade. Although it was understood that access to study participant's medical records was prohibited, future military studies should consider the use of the NISS supported with medical records and imaging for this population to determine injury severity and effect on high-level mobility.

The use of AMPPro items as surrogate measures of lower-limb strength, balance, and gait components has been reported in previous literature to predict prosthetic mobility [7]. For this study, the AMPPro items were effective in determining the relative contribution of the previously mentioned factors to high-level mobility capabilities. Yet, future research should consider using direct measures of lower-limb power, balance, and gait to determine contribution to high-level mobility. In addition, functional strength measures of the hip extensors, hip abductors, and plantar flexors have been used in previous literature to predict functional mobility [6–7,58]. Future research should examine hip extensor, hip abductor, and plantar flexor functional strength as a predictor of CHAMP score for SMs with unilateral amputation and BLLA. Lastly, the ability to examine interlimb symmetry when performing high-level mobility provides the clinicians and SMs with information about current strategies used and could help guide an intervention to address asymmetrical movements or reinforce positive strategies. Future research should examine the use of clinical tools, such as symmetry of external work to determine interlimb symmetry during high-level mobility for SMs with traumatic LLL [59].

CONCLUSIONS

The purpose of this study was to examine the possible relationship between ability to perform high-level mobility and factors modifiable by rehabilitation interventions and other factors related to LLL in SMs with traumatic LLL.

Our findings demonstrated the importance of salvaging the knee joint whenever possible. Intact knee joints provide the SM with the ability to utilize lower-limb musculature as biomechanically intended, thereby increasing the possibility of returning to high-level mobility activities following rehabilitation. We also found that rehabilitation-related factors such as lower-limb strength, standing and dynamic balance, and ability to displace the CoM over the base of support were all significantly related to ability to perform high-level mobility activities. This suggests that rehabilitation interventions designed to improve lower-limb and trunk strength, dynamic balance over the prosthesis, and lower-limb and trunk flexibility could improve high-level mobility in SMs with TTA, TFA, and BLLA. Findings related to central adiposity suggest that rehabilitation interventions to improve general cardiovascular fitness may also improve high-level mobility by increasing general fitness and decreasing adipose body mass. After controlling for rehabilitation factors and other factors, the J-shaped ESAR feet may improve high-level mobility in SMs with TTA. It is our hope that these findings will help guide the rehabilitation and aid in the development of appropriate interventions for SMs with traumatic LLL in an effort to achieve maximum high-level mobility capabilities.

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