

INTRODUCTION

The loss or absence of a limb is a serious bodily impairment caused by disease, trauma, or congenital disorder. Current estimates indicate that upper- and lower-limb loss (LLL) affects more than 1.6 million individuals living in the United States [1]. The rising incidence of dysvascular amputation, most recently reported in the period between 1988 and 1996 [2], has contributed to an overall 19 percent increase in persons with limb loss between 1996 and 2005 [1,3]. Moreover, the aging population and growing incidence of health conditions such as obesity, diabetes, and dysvascular disease are predicted to elevate the prevalence of limb loss in the United States to more than 3.6 million individuals by the year 2050 [1]. This trend insinuates not only a need to improve preventative care, research, and education related to limb loss but also the means to provide appropriate assistive technology to a growing population of individuals facing acute physical challenges.

The most severe form of physical impairment associated with limb loss or absence traditionally involves major (i.e., nondigit) loss of the limb. More than 42 percent of all amputations are attributed to major limb loss, with the vast majority (approximately 94%) [1] occurring in the lower limb. Given the importance of the lower limb to balance, transfer, and ambulation activities, LLL negatively affects an individual's functional ability at home and in the community [4–9]. For example, a 2006 systematic review of walking ability following LLL noted that, while 56 to 97 percent of individuals regain walking ability following LLL, only 26 to 62 percent regain the ability to ambulate outdoors [4]. This specific limitation seems critical because an inability to ambulate outside of the home may impede participation in both vocational and avocational activities and increase reliance on physical, personal, and financial assistance.

The physiological and functional challenges associated with LLL are also exacerbated at more proximal levels of LLL [8,10–13], as evidenced by significantly fewer individuals with transfemoral limb loss (TFLL) than individuals with transtibial limb loss who are reported to achieve household (50% vs 66%) or community (29% vs 54%) ambulation [8]. TFLL, when compared with LLL at more distal levels, has also been reported to be associated with a decreased frequency of prosthetic fitting [7,14–15] and an increased frequency of back, knee, and hip pain [16–19]; obesity [20]; and osteoarthritis [17,21].

These medical issues may ultimately contribute to the extended period of disability and failure to return to work that have been associated with TFLL [22].

Among the many documented functional challenges facing individuals with TFLL, those commonly cited include decreased balance [23–29]; increased metabolic energy expenditure while walking [30–34]; decreased walking speed [31,33,35–36]; gait asymmetries [35–38]; increased frequency of stumbles and falls [27,39]; reduced activity level [40–42]; difficulty negotiating uneven terrain, hills, and stairs [23,43–45]; and increased cognitive demand while walking [46–47]. LLL may also affect patients' health-related quality of life (HRQL), as suggested by lower 36-Item Short-Form Health Survey (SF-36) scores [48–51] among individuals with TFLL than nondisabled individuals [52–53]. Correspondingly, surgical, medical, therapeutic, and prosthetic interventions that address these challenges are considered important to the successful rehabilitation of individuals with TFLL.

A wide variety of prosthetic interventions are available to address functional limitations that result from LLL [54–58]. For individuals with TFLL, selecting an appropriate prosthetic knee is considered to be a critical element in the successful outcome of a patient [59]. A prosthetic knee is typically chosen to provide both the stability and agility users require for balancing and ambulating effectively. Although more than 220 different prosthetic knee products are available to address the breadth of individual user needs [60], no universal system for classification exists to describe the function, features, or benefits of individual prosthetic knees. Clinical conventions in use today often categorize prosthetic knees according to the hinge type and control system inherent in the unit [59,61]. Additionally, a prosthetic knee's stability behavior (i.e., stance control) is commonly described independently from those features that provide agility (i.e., swing control) to provide a complete overview of the prosthetic knee's function.

Traditional prosthetic knees are available in either single-axis or polycentric designs. Stance stability for these is determined by the position of knee joint (single-axis hinge) or instant center of rotation (polycentric hinge) with respect to the ground reaction force (GRF) vector and is commonly augmented by inherent features such as a mechanical lock, mechanical friction brake, and/or hydraulic resistance mechanism. The prosthetic knee's agility in swing may similarly be supplemented with intrinsic features such as a mechanical friction brake,

elastic extension assist, and/or fluid (i.e., hydraulic or pneumatic) that act to regulate resistance of the knee joint, thereby contributing to a user's ability to vary his or her cadence and walking speed. The behavior is then set by a prosthetist through mechanical adjustments to the alignment and/or the intrinsic stance and swing features of the prosthetic knee. Once these parameters have been fixed, the prosthetic knee will perform consistently in response to the loading conditions with which it is presented.

Contemporary prosthetic knees also include models that incorporate a microprocessor (MP) within the unit [62]. These MP-controlled prosthetic knees (MPKs), while similar in basic function (i.e., stability in stance, agility in swing) to non-MP-controlled prosthetic knees (NMPKs), allow the MP to perpetually "fine-tune" many of the prosthetic knee's intrinsic behaviors. This allows an MPK to resist or allow flexion in response to load, position, and/or velocity sensors. This technology is intended to make the prosthetic knee responsive to the user's instantaneous needs (i.e., allow him or her to change cadence and walking speed) and adjust its behavior (i.e., provide more or less knee-flexion resistance) in response to extrinsic conditions, thereby mimicking the behavior of a nondisabled knee.

Note that there are a variety of MPKs available and that the control afforded to the MP differs among prosthetic knees. For example, some MPKs regulate only the stance behavior (e.g., Compact C-Leg, Otto Bock; Minneapolis, Minnesota) and some regulate only the swing behavior (e.g., SmartIP, Endolite; Miamisburg, Ohio), while others regulate both the stance and swing behavior (e.g., Compact C-Leg and RHEO KNEE; Össur Americas; Foothill Ranch, California). In general, the more control afforded to the MP, the greater the sophistication and cost of the device. However, inclusion of an MP into the prosthetic knee is believed to provide a number of theoretical benefits to the user, including improvements in balance, confidence, uneven terrain ambulation, stair descent, incline negotiation, and overall activity, as well as a reduction in adverse events such as stumbles and falls.

Although MPKs have been clinically available and actively prescribed for individuals with TFL for more than 15 yr [63], the body of research related to these devices is relatively small and diverse. The number of published, peer-reviewed research studies in this area has grown in recent years, but widespread translation of this knowledge for clinical and scientific purposes has yet to occur. Thus, it seems an opportune time to systematically

review, critically evaluate, and appropriately synthesize the body of knowledge in order to address this need. At the time of this review (October 2009), no such endeavor had been undertaken. Specifically, no comprehensive, peer-reviewed systematic evaluation of the effectiveness of MPKs in the rehabilitation of individuals with TFL had been identified. Such information would be immediately useful to inform clinical practice, advise reimbursement decisions, and direct future research.

The purpose of this systematic review was therefore to evaluate the state of the science in MPK research and to synthesize this knowledge for dissemination. Such information could then be used to form evidence-based practice (EBP) clinical guidelines regarding the safe and effective implementation of this rapidly evolving technology and to develop future research questions. We carefully constructed a specific question to address these aims and to direct this systematic review. We developed the question using the PICO (Patient/Population Intervention Comparison Outcome) method [64], a recognized technique for developing a well-built and clinically relevant question [64–66]. We also phrased the question in a neutral manner to avoid bias toward the efficacy of the intervention and allow for an objective assessment of the scientific literature. For the purposes of this review, we elected to answer the question, Does the prescription, fit, and use of MPKs lead to changes in outcomes for individuals with unilateral TFL when compared with NMPKs?

METHODS

Literature Search

We conducted a systematic search of the literature in October 2009 using several healthcare and biomedicine databases, including PUBMED (1949 to October 2009), CINAHL (1981 to October 2009), RECAL Legacy (early 1900s to October 2009), and the Cochrane Library (1996 to October 2009). We searched the databases using generic key words related to MPKs and augmented with specific terms related to two specific prosthetic knee products, the Compact C-Leg and SmartIP, that we knew to be the focus of multiple, independent scientific research studies. We combined the key words into a single search phrase using Boolean operators to standardize the search across the databases. The syntax used in the PUBMED, CINAHL, and Cochrane Library databases was as follows: ((microprocessor AND knee AND prosth*) OR (C-Leg) OR (intelligent

AND prosth*)). We amended the search of the RECAL Legacy database by removing the search term “C-Leg” because its use was interpreted by the database as the term “leg,” thus resulting in an excessive number of unrelated results. We also identified additional manuscripts by searching references of initially included publications.

Inclusion and Exclusion Criteria

We established specific a priori inclusion and exclusion criteria in order to select those publications that met specific criteria, were written in or translated into English, and were relevant to the stated purpose of the review. We restricted publications to those published in peer-reviewed journals. We did not include conference proceedings, white papers, theses, or dissertations. We did not limit publications by study design or methodological quality, and we considered all structured reviews, experimental trials, and observational studies [67] for inclusion to adequately consider the overall state of the science in this area.

We similarly developed inclusion and exclusion criteria pertaining to study interventions and populations to select those most suited to answering the guiding question of this review. We included studies that compared any type of MPK (i.e., swing-phase MP control [MPC], stance-phase MPC, or swing and stance MPC) with any type of NMPK. Similarly, we considered studies that included subjects with TFLL or knee disarticulation LLL because both MPKs and NMPKs are prescribed and fit to these subjects and sagittal-plane control of a prosthetic knee at either level is based on similar biomechanical principles. Conversely, we excluded studies that included individuals with bilateral LLL to avoid confounding factors related to bilateral involvement. Although MPKs are prescribed for individuals with bilateral LLL, biomechanical performance and function of individuals with bilateral LLL differs greatly from those with unilateral LLL [33,68–69]. Similarly, we excluded studies of subjects who required walking aids, such as crutches, canes, or walkers, to avoid potentially confounding factors related to ambulation with an assistive device [33,70]. We applied no exclusion criteria based on the LLL etiology of study subjects. Lastly, we included studies with individuals aged ≥ 16 yr because this is the population for whom MPKs are currently designed.

Assessment of Methodological Quality

We independently appraised the study design and methodological quality of those publications that met the inclusion and exclusion criteria according to guidelines developed by the American Academy of Orthotists and Prosthetists (AAOP) [71]. When we could not obtain consensus regarding either methodological quality or study design, we discussed the relevant issues until we achieved consensus. In situations where there existed a perceived conflict of interest, an alternate qualified reviewer participated in the assessment of the study methodological quality. This situation occurred in two instances when one of the authors (B.H.) was a contributing author to the reviewed publications [72–73].

We classified study design according to the AAOP Study Design Classification Scale, a 15-level categorization scheme based on the type of described study [71]. In situations where a single publication described multiple types of study designs, we assigned the overall classification according to the predominant study design. We rated study methodological quality using the State of the Science Conference (SSC) Quality Assessment Form, two checklists developed to facilitate standardized assessment of internal validity (IV) and external validity (EV) across multiple studies [71]. The SSC Quality Assessment Form identifies up to 18 potential threats to IV and 8 potential threats to EV that may be relevant to the study designs noted in the AAOP Study Design Classification Scale. We independently evaluated each criterion on the SSC Quality Assessment Form, which were deemed to be “met” (noted with a “●” in **Table 1**) if the publication addressed the specified threat. **Appendixes 1** and **2** (available online only) provide a description of the information that was required to be presented in the publication in order to meet each criterion. Note that we deemed a number of methodological criteria to be “not applicable” to selected study designs [71]. For example, IV criteria 1 to 4 and 12 pertain only to experimental group study designs (i.e., randomized controlled trial [E₁] or controlled trial [E₂]). **Appendixes 1** and **2** show details regarding those IV and EV criteria we deemed to be applicable to each type study design.

We then rated the IV and EV of each publication as “high,” “moderate,” or “low.” We generally rated publications high for IV or EV if none or one of the criterion were not met and any that were not met posed minimal risks to validity (e.g., criterion EV-5: “intervention adequately described”). We rated publications as moderate for IV or

Table 1.
Internal validity (IV) and external validity (EV) of included studies.

Publication	Study Design	IV Criterion																EV Criterion								Overall		
		1-4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total	1	2	3	4	5	6	7	8		Total	
Kirker et al. (1996) [80]	E ₅	NA	•				•	•	NA		•	•	•	•	•	•	Low	•	•	•	•	•	•	•	•	Mod	Low	
Taylor et al. (1996) [84]	E ₅	NA	•		NA	NA	•	•	NA	NA				•	NA		Low	•	•	•	•	•	•	•	•	Low	Low	
Buckley et al. (1997) [75]	E ₅	NA	•				•	•	NA							•	Low	•	•	•	•	•	•	•	•	Low	Low	
Datta & Howitt (1998) [88]	O ₃	NA	NA	NA			NA	•	•	NA			•	NA			Low	•	•	•	•	•	•	•	•	Mod	Low	
Heller et al. (2000) [95]	E ₅	NA	•				•	•	•	NA			•	•		•	Mod	•	•	•	•				•	Low	Low	
Schmalz et al. (2002) [82]	E ₅	NA	•				•			NA			•	•			Low	•	•	•	•	•			•	Mod	Low	
Herr & Wilkenfeld (2003) [96]	E ₅	NA	•				•	•	NA								Low		•	•	•	•			•	Low	Low	
Yokogushi et al. (2004) [99]	E ₅	NA	•				•	•	NA					•		•	Low	•	•	•	•	•	•	•	•	Low	Low	
Datta et al. (2005) [76]	E ₅	NA	•				•	•	NA				•	•		•	Low	•	•	•	•	•	•	•	•	Mod	Low	
Johansson et al. (2005) [78]	E ₅	NA	•				•	•	NA				•	•			Low	•	•	•	•	•	•	•	•	Mod	Low	
Segal et al. (2006) [98]	E ₅	NA	•				•	•	NA				•	•	•	•	Low	•	•	•	•	•	•	•	•	Mod	Low	
Orendurff et al. (2006) [81]	E ₅	NA	•				•	•	NA				•	•		•	Low	•	•	•	•	•	•	•	•	Mod	Low	
Klute et al. (2006) [91]	E ₅	NA	•		•	•	NA	•	NA	•	•		•	•		•	Mod	•	•	•	•	•	•	•	•	•	Low	Low
Williams et al. (2006) [94]	E ₅	NA	•		•	•		•	NA	•	•	•	•	•		•	Mod		•	•	•	•	•	•	•	•	Mod	Mod
Kaufman et al. (2007) [97]	E ₅	NA	•		•	•		•	•	NA	•	•		•			Mod	•	•	•	•	•	•	•	•	•	High	Mod
Seymour et al. (2007) [83]	E ₅	NA			•	•	•			NA	•	•		•			Low	•	•	•	•	•	•	•	•	•	High	Low
Hafner et al. (2007) [73]	E ₅	NA			•	•		•	•	NA	•	•		•			Low	•	•	•	•	•	•	•	•	•	Mod	Low
Stevens & Carson (2007) [103]	O ₆	NA	NA	NA	NA	NA	NA	•	NA	NA	•	•	NA	NA	NA	•	High	•	•	•	•	•	•	•	•	•	Low	Low
Jepson et al. (2008) [77]	E ₅	NA			•	•		•	NA				•	•		•	Mod		•	•	•	•	•	•	•	•	Low	Low
Kahle et al. (2008) [90]	E ₅	NA			•			•	•	NA	•		•	•		•	Low	•	•	•	•	•	•	•	•	•	Mod	Low
Kaufman et al. (2008) [79]	E ₅	NA	•		•	•		•	•	NA	•		•	•			Mod	•	•	•	•	•	•	•	•	•	High	Mod
Gerzeli et al. (2009) [89]	O ₃	NA	NA	NA	•		NA	•	NA	NA	•	•		•			Mod	•	•	•	•	•	•	•	•	•	Mod	Mod
Brodtkorb et al. (2008) [105]	O ₃	NA	NA	NA	•		NA	•	NA	NA							Low		•	•	•	•			•	•	Low	Low
Seelen et al. (2009) [92]	O ₃	NA	NA	NA	•	•	NA		NA	NA			•	NA	•	•	Mod	•	•	•	•	•	•	•	•	•	High	Mod
Berry et al. (2009) [101]	O ₃	NA	NA	NA	•		NA	•	NA	NA	•		NA	•		•	Mod	•	•	•	•	•	•	•	•	•	Mod	Mod
Hafner & Smith (2009) [72]	E ₅	NA			•	•		•	•	NA	•		•	•			Low	•	•	•	•	•	•	•	•	•	Mod	Low
Blumentritt et al. (2009) [102]	E ₅	NA	•				•	•	NA					NA			Low	•	•	•	•	•	•	•	•	•	Low	Low
Threat Addressed		NA	16	0	13	9	7	22	12	0	6	30	1	19	1	15	—	23	7	27	18	21	24	23	21	—	—	
Threat Applicable		NA	21	21	25	25	20	27	20	0	27	27	24	26	23	27	—	27	27	27	27	27	27	27	27	—	—	

Note: Description of IV criterion: 5. Control group or comparison appropriate; 6. Intervention(s) blinded; 7. Inclusion criteria appropriate; 8. Exclusion criteria appropriate; 9. Protocol addresses fatigue and learning; 10. Protocol addresses accommodation and washout; 11. Attrition explained and less than 20%; 12. Attrition equal between groups; 13. Outcome measures reliable; 14. Statistical analysis appropriate; 15. Effect size reported; 16. Statistical significance reported; 17. Statistical power adequate; 18. Free from conflicts of interest. Description of EV criterion: 1. Sample characteristics adequately described; 2. Sample representative of target population; 3. Outcome measures adequately described; 4. Outcome measures valid for this study; 5. Intervention adequately described; 6. Findings clinically significant/relevant; 7. Conclusions placed in context of existing literature; 8. Conclusions supported by findings.

E₅ = controlled before-and-after trial, Mod = moderate, NA = particular threat to IV or EV not applicable to particular study design, O₃ = cross-sectional study, O₆ = case study, • = threat to IV or EV was adequately described in publication, blank = threat to IV or EV was not adequately described in publication.

EV if more than one but less than half of the applicable criteria were not met. We rated publications as low when half or more of the applicable criteria were not met. We instituted two exceptions to these rules. First, we deemed publications ineligible for a high EV rating if the study sample included 10 or fewer participants. Second, we deemed publications ineligible for a moderate EV rating if the study sample included five or fewer participants. We instituted these exceptions to reflect the inherent difficulties in generalizing results from small samples to a larger population even when other threats to EV are addressed. Although this objective method for assigning ratings of methodological quality differs slightly from recommendations described in the AAOP Study Design Classification Scale [71], we considered this to be a fair and reasonable approach to evaluating a publication's contributions to the overall evidence. Sanders and Fatone recently described a similar approach to application of the AAOP Study Design Classification Scale methodological criterion [74].

Lastly, we assigned publications a "high," "moderate," or "low" overall methodological quality rating. We defined overall ratings according to the lower of the IV and EV ratings to reflect a conservative estimate of the evidence provided by the publication. We used a publication's overall rating to justify the level of evidence that exists to support developed empirical evidence statements (EESs).

Empirical Evidence Statements

We used results obtained from individual publications that compared MPKs with NMPKs to develop the EESs. We grouped them into nine outcome topics: (1) metabolic energy expenditure, (2) activity, (3) cognitive demand, (4) gait mechanics, (5) environmental obstacle negotiation, (6) safety, (7) preference and satisfaction, (8) economics,

and (9) health and quality of life (QOL). For each topic, we developed specific EESs to summarize the statistically significant findings reported in the reviewed literature. We based EESs on the findings from the research and the type of MPK (i.e., swing-phase MPC, stance-phase MPC, or swing and stance MPC) to which those results applied. We developed EESs when two or more studies reported results pertaining to a single outcome. We did not include additional demographic descriptors such as etiology, age, or activity level within the EESs because of inconsistent reporting of such variables across the reviewed body of literature. We determined the directionality (i.e., increased, decreased, or equivalent) of each EES by those studies that reported statistically significant findings related to the developed EES. We then substantiated each EES by examining (1) the number of publications contributing to the EES, (2) the overall methodological quality of those studies, and (3) whether the contributing findings were confirmatory or conflicting. Based on these three criteria, we qualified each EES with a level of evidence. We defined the levels of evidence a priori as "high," "moderate," "low," or "insufficient" according to the definitions in **Table 2**. Note that, in situations where we believed multiple publications described the same study (i.e., same investigators, same group of subjects) and contributed to the same EES, the results of both publications did not strengthen the level of evidence.

RESULTS

Literature Search

The described search strategy yielded 241 unique citations across the four chosen databases. Of these, we

Table 2.
Definitions of level of evidence supporting empirical evidence statements.

Evidence Level	Definition
High	Reviewers found high level of evidence to support statement based on findings from multiple independent peer-reviewed studies of moderate to high overall methodological quality that demonstrate consistent results in support of statement.
Medium	Reviewers found moderate level of evidence to support statement based on findings from multiple independent peer-reviewed studies of low to moderate overall methodological quality that demonstrate consistent results in support of statement.
Low	Reviewers found low level of evidence to support statement based on findings from multiple peer-reviewed studies of low methodological quality or presence of substantial findings that are inconsistent with statement.
Insufficient	Reviewers found insufficient evidence to support statement due to multiple studies with conflicting results.

initially selected 69 based on a review of their titles. We added two additional publications from searching the references in these initial 69 publications. Upon review of the abstracts (and full-length manuscripts, as necessary), 27 of the 71 publications met the a priori inclusion and exclusion criteria established for this review. The included publications spanned the years 1996 to 2009. Of the 27 included publications, nearly two-thirds were published after 2005. The publications selected for review were predominantly sourced from rehabilitation or orthotic and prosthetic (O&P) peer-reviewed journals. Several were published in journals that focused on engineering, economics, and human movement.

Study Demographics

We classified the reviewed studies into 5 of the 15 potential designs described by the AAOP Study Design Classification Scale [71], including controlled before-and-after trials, case-controlled studies, cross-sectional studies, case series, and case studies. Sample sizes ranged from 1 to 368 (mean = 27, median = 8). The cause of LLL in study subjects was predominantly (i.e., approximately 90 percent of all subjects) nondysvascular (i.e., trauma, tumor, osteomyelitis, congenital, or other). The description of study subjects' activity level or ability to ambulate was often vague in studies published prior to 2005. However, we believed subjects across this body of literature to be at the level of a community ambulator (i.e., Medicare Functional Classification Level [MFCL]-2) or higher based on the descriptions provided.

All of the studies published prior to 2001 included swing phase-only MPKs as the intervention of interest; the vast majority of manuscripts (20 of 22) published after 2001 focused on swing and stance MPKs. In total, 20 of the 27 reviewed publications described comparisons between swing and stance MPKs and NMPKs, while the remaining 7 described comparisons between swing phase-only MPKs and NMPKs. No study that met the described selection criteria included both types of MPKs. Outcomes reported in the reviewed publications included metabolic energy expenditure, activity, cognitive demand, gait mechanics, negotiation of environmental obstacles, safety, preference and satisfaction, economics, and health and QOL. Most publications described more than one outcome.

Methodological Quality Assessment

Assessment of overall methodological quality, based on the aforementioned approach, identified 21 publica-

tions of low and 6 of overall moderate methodological quality. The publications' IV scores, rather than their EV scores, were often the reason why overall methodological quality was reduced (**Table 1**). Among the 17 publications that we determined to have moderate or high EV, we assigned 11 low overall methodological quality as a result of low IV. Conversely, of the 10 publications that we noted to have moderate or high IV, we assigned 4 low overall methodological quality because of low EV.

Empirical Evidence Statements

Based on the findings reported in the 27 reviewed studies, we created and organized 28 EESs into 9 outcome topics. We wrote the EESs to indicate the extent to which the empirical evidence suggests that the prescription and use of MPKs results in changes to rehabilitation-related outcome measures among individuals with unilateral TFL when compared with the use of NMPKs. Each of the EESs is accompanied by a level of evidence that indicates the degree to which the accumulated evidence supports it. Note that we generalized EESs developed for this review to the population of individuals with unilateral TFL. Refer to **Table 3** for additional study and subject demographics that may inform the generalizability of the EES to specific individuals.

Metabolic Energy Expenditure

Metabolic energy expenditure outcomes are those associated with measures of the physiological energy requirements of ambulation. Measures of energy expenditure reported in the MPK literature include oxygen (O_2) cost, O_2 rate, total daily energy expenditure (TDEE), physical activity-related energy expenditure (PAEE), physiological cost index (PCI), and rating of perceived exertion (RPE) [75–84].

O_2 cost, the O_2 consumed (normalized to body weight) per unit distance traveled during ambulation has been reported in the literature for comparisons between NMPKs and both swing and stance [79,81,83] and swing-only MPKs [75–76]. O_2 cost was measured primarily while subjects walked at a self-selected walking speed (SSWS) and/or at a controlled walking speed (CWS) on a treadmill [75–76,79,83]. However, one study measured this outcome as subjects walked over level ground in a laboratory [81]. Comparisons between swing and stance MPKs and NMPKs showed mixed results. In two studies, NMPK users were transitioned to the swing and stance MPK in either a sequential or randomized

Table 3.
Characteristics of included studies.

Publication	Study Design	Intervention (MPK)	Comparison (NMPK)	Sample Size (n)	Age (yr)*	Etiology (n)	Activity or Functional Level	Time Since Limb Loss (yr)*	Outcome Topic
Kirker et al. (1996) [80]	E ₅	Weight-activated locking (ST); MP fluid (SW)	Weight-activated locking (ST); Pneumatic (SW)	6	36.5 (29–44)	Traumatic (ND); Congenital (ND)	Regularly walk at different speeds	16.5 (7–44)	1, 4, 7
Taylor et al. (1996) [84]	E ₅	Weight-activated locking (ST); MP fluid (SW)	Various	1	33.0	Traumatic (1)	Active	NR	1
Buckley et al. (1997) [75]	E ₅	Weight-activated locking (ST); MP fluid (SW)	Weight-activated locking (ST); Pneumatic (SW)	3	NR (39–59)	Traumatic (3)	Fit/active	NR	1
Datta & Howitt (1998) [88]	O ₃	Weight-activated locking (ST); MP fluid (SW)	Weight-activated locking (ST); Pneumatic (SW)	22	39.9 (25–76)	Traumatic (16); Tumor (5); Osteomyelitis (1)	Fairly active	19.2 (5–53)	2, 7
Heller et al. (2000) [95]	E ₅	Weight-activated locking (ST); MP fluid (SW)	Weight-activated locking (ST); Pneumatic (SW)	10	38.0 (23–46)	Traumatic (8); Tumor (2)	NR	>5 (NR)	3
Schmalz et al. (2002) [82]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	6	37.0 (27–53)	Traumatic (6)	NR	13.0 (1–29)	1
Herr & Wilkenfeld (2003) [96]	E ₅	MP fluid (ST); MP fluid (SW)	Various	4	39.0 (25–48)	NR (4)	NR	>2 (NR)	4
Yokogushi et al. (2004) [99]	E ₅	Fluid (ST); MP fluid (SW)	Position locking (ST); Hydraulic (SW)	3	28.0 (NR)	Traumatic (3)	NR	>3 (NR)	4
Datta et al. (2005) [76]	E ₅	Weight-activated locking (ST); MP fluid (SW)	Weight-activated locking (ST); Pneumatic (SW)	10	38.0 (23–46)	Traumatic (8); Tumor (2)	NR	>5 (NR)	4
Johansson et al. (2005) [78]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	8	NR (29–54)	Traumatic (3); Tumor (2); Infection (2); Congenital (1)	MFCL ≥K3	NR	1, 4
Segal et al. (2006) [98]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	8	47.0 (28–60)	Traumatic (8)	NR	>3 (NR)	4
Orendurff et al. (2006) [81]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	8	48.5 (29–61)	Traumatic (8)	NR	>3 (NR)	1, 4, 7
Klute et al. (2006) [91]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	5	48 (NR)	Traumatic (4); Tumor (1)	Community ambulators	21 (NR)	2
Williams et al. (2006) [94]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	8	48.5 (29–61)	NR (8)	NR	NR	3
Kaufman et al. (2007) [97]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	15	42.0 (26–57)	Traumatic (7); Tumor (6); PVD (1); Congenital (1)	MFCL K4	20.0 (3–36)	4
Seymour et al. (2007) [83]	E ₅	MP fluid (ST); MP fluid (SW)	Various	13	46 (30–75)	Nonvascular (13)	MFCL K4	NR	1, 5
Hafner et al. (2007) [73]	E ₅	MP fluid (ST); MP fluid (SW)	Various	17	48 (21–77)	Traumatic (10); Tumor (3); Infection (2); PVD (1); Deformity (1)	MFCL K2–K3	17.65 (2–67)	2–8
Stevens & Carson (2007) [103]	O ₆	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	1	30.0	Traumatic (1)	Participated in running and cycling	3 mo (NR)	6
Jepson et al. (2008) [77]	E ₅	MP fluid (ST); MP fluid (SW)	Hydraulic (ST); Hydraulic (SW)	5	41.2 (28.8–55.7)	NR (5)	NR	NR	4, 6–7
Kahle et al. (2008) [90]	E ₅	MP fluid (ST); MP fluid (SW)	Various	19	51.0 (22–83)	Traumatic (7); PVD (3); Diabetes (4); Congenital (4); Tumor (1)	MFCL ≥K2	NR (3–36)	2, 4–7
Kaufman et al. (2008) [79]	E ₅	MP fluid (ST); MP fluid (SW)	Various	15	42.0 (26–57)	Traumatic (7); Tumor (6); PVD (1); Congenital (1)	MFCL K4	20.0 (3–36)	1–2, 8
Gerzeli et al. (2009) [89]	O ₃	MP fluid (ST); MP fluid (SW)	NS	100	45.8 (NR)	Dysvascular (4); Traumatic (96)	Daily use (hr): MPK: 13.5; NMPK: 11.7	13.7 (NR)	2, 9
Brodtkorb et al. (2008) [105]	O ₃	MP fluid (ST); MP fluid (SW)	NS	20	41.0 (NR)	NR	NR	16.0 (NR)	9
Seelen et al. (2009) [92]	O ₃	MP fluid (ST); MP fluid (SW)	Various	26	47.0 (NR)	Dysvascular (5); Traumatic (16); Tumor (5)	NR	MPK: 13.2; NMPK: 11.4 (NR)	2, 8–9
Berry et al. (2009) [101]	O ₃	MP fluid (ST); MP fluid (SW)	Various	368	54.7 (15–85)	Mixed (368)	MFCL K3	NR (0.2–78.7)	6
Hafner & Smith (2009) [72]	E ₅	MP fluid (ST); MP fluid (SW)	Various	17	48.0 (21–77)	Traumatic (10); Tumor (3); Infection (2); PVD (1); Deformity (1)	MFCL K2–K3	17.65 (2–67)	2–3, 5–6, 8
Blumentritt et al. (2009) [102]	E ₅	MP fluid (ST); MP fluid (SW)	Various	3	NA(25–43)	Traumatic (2); Tumor (1)	MOBIS 3–4	19 (9–26)	6

*Mean (range).

Note: Outcome topics: 1. metabolic energy expenditure, 2. activity, 3. cognitive demand, 4. gait mechanics, 5. environmental obstacle negotiation, 6. safety, 7. preference and satisfaction, 8. health and quality of life, 9. economics.

E₅ = controlled before-and-after trial, MFCL = Medicare Functional Classification Level, MOBIS = Mobility System, MP = microprocessor, MPK = microprocessor-controlled knee, NA = particular threat to internal or external validity not applicable to particular study design, ND = not defined, NMPK = non-microprocessor-controlled knee, NR = not reported, NS = not specified, O₃ = cross-sectional study, O₆ = case study, PVD = peripheral vascular disease, ST = stance-control mechanism, SW = swing-control mechanism.

order and no significant difference in O_2 cost between interventions at either SSWS or CWS was reported [79,81]. Users were provided with at least 10 wk to accommodate to the MPK in these studies. A study of active (i.e., MFCL-4) and established MPK users found that significantly increased O_2 costs were incurred when users wore the NMPK prosthesis at SSWS and CWS [83]. Subjects were given 5 min to accommodate to the NMPK prosthesis before testing. A single study of 10 subjects reported a decrease in O_2 cost when subjects wore a swing-only MPK compared with an NMPK [76]. The difference was reported as significant, but only at speeds below SSWS. No accommodation to the MPK outside of the test session was provided.

O_2 rate, the O_2 consumed (normalized to body weight) per unit time of steady-state physical activity, was similarly reported in a number of studies comparing NMPKs with both types of MPKs [78,80,82–84]. Three studies of between 6 and 10 subjects reported significantly reduced O_2 rates at SSWS when the users wore the swing and stance MPK compared with the NMPK [78,82–83]. Two studies that reported results for fast walking speeds conflicted, because one found a significant decrease in O_2 rate while using a swing and stance MPK when compared with the NMPK [83], while the other found no significant difference between the interventions [82]. Several smaller studies consisting of one to six subjects reported no significant differences in O_2 rate when individuals used a swing-only MPK compared with using NMPKs [75,80,84]. All of the O_2 rate studies tested both interventions on the same day [75,80,84].

Kaufman et al. [79] examined metabolic energy expenditure in the free-living environment using a doubly labeled water (DLW) technique [85]. Subjects were monitored over 10 d periods as they used either a swing and

stance MPK or a swing and stance NMPK. Kaufman et al. used the obtained data to calculate each subject's TDEE and PAEE over the observation period. They reported that subjects' overall TDEE did not significantly differ between interventions, but the metabolic energy expenditure associated with activity significantly increased while subjects wore the MPK prosthesis.

One study [77] of four subjects wearing swing and stance MPKs and NMPKs examined energy expenditure by measuring PCI [86]. Jepson et al. tested subjects in their existing NMPKs and then again after 8 wk of accommodation to the MPK. They reported that three subjects showed an increased PCI using the MPK; the other subject showed no difference between interventions [77].

Lastly, one study [79] of 15 subjects examined subject-reported energy expenditure using the Borg RPE [87]. Subjects, who were accommodated to both prostheses at the time of assessment, reported a significantly lower RPE while using a swing and stance MPK than an NMPK after walking on a treadmill [79].

Table 4 shows the EESs we developed related to metabolic energy expenditure outcomes.

Activity

Activity outcomes are those associated with mobility or physical function in the free-living environment over an extended period of time. Measures of activity reported in the MPK literature include step counts; frequency of activity bouts; activity bout duration; and a variety of patient-reported outcomes (PROs) including the Prosthesis Evaluation Questionnaire (PEQ) ambulation subscale, SF-36 physical function subscale, EuroQol physical mobility subscale, and subject-reported walking ability [72–73,79, 88–92].

Table 4.
Metabolic energy expenditure empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
1-A. Use of swing and stance MPKs results in equivalent O_2 cost (at self-selected, slow, and fast speeds) compared with use of NMPKs among individuals with unilateral TFL.	1 × Moderate [79] 2 × Low [81,83]	Moderate
1-B. Use of swing and stance MPKs results in decreased O_2 rate (at self-selected walking speed) compared with use of NMPKs among individuals with unilateral TFL.	3 × Low [78,82–83]	Low
1-C. Use of swing-only MPKs results in equivalent O_2 rate (at self-selected, slow, and fast speeds) compared with use of NMPKs among individuals with unilateral TFL.	3 × Low [75,80,84]	Low

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, O_2 = oxygen, TFL = transfemoral limb loss.

Two studies assessed temporal measures of physical activity outside of the laboratory environment (i.e., step counts, activity bout frequency, and/or activity bout duration) [73,91] using a step activity monitor [93]. Both studies compared a swing and stance MPK with an NMPK as study subjects used the prosthetic knees in a free-living environment. The period of activity assessment ranged from 1 [91] to 2 [73] wk, and the prosthetic knees were provided to study subjects in either a sequential [73] or randomized order [91]. In both cases, the publication reported no significant differences in step-related activity outcomes between the interventions [73,91].

In contrast to objective measures of activity, subjects' self-reported activity was found to differ when using an MPK compared with an NMPK. Several investigators reported a significant increase in the PEQ Addendum (PEQ-A) for subjects using a swing and stance MPK compared with the NMPK [72,79,90]. Similarly, self-reported physical function, as measured by the SF-36 physical function subscale, showed significantly higher scores with a swing and stance MPK than an NMPK [89,92].

Table 5 shows the EESs we developed related to activity outcomes.

Cognitive Demand

Cognitive demand outcomes are those associated with the physiological or perceived cognitive burden of locomotion. Physiological measures of cognitive demand reported in the MPK literature include distance traveled during a divided attention task, SSWS during a divided attention task, sway velocity during a divided attention task, serial subtraction test, Controlled Oral Word Association Test, and the Category Test. Perceived measures of cognitive demand that have been reported include the PEQ-A and the Prosthetic Cognitive Burden Scale (PCBS) [72–73,80,94–95].

Objective tests of divided attention have rarely reported significant differences in physiological measures of the cognitive demand required for ambulation when comparing MPKs and NMPKs [72–73,94–95]. No consistent measure of cognitive demand was used across the reviewed studies, but all included a measure of performance (e.g., head sway, accuracy of responses, number of correct responses) as subjects walked while performing a secondary (i.e., unrelated) task. The difficulty of the secondary tasks likewise varied across studies. No significant differences between the MPK and NMPK conditions were measured for users of swing-only MPKs walking on a treadmill [95], swing and stance MPK users walking in a laboratory [94], or swing and stance MPK users walking outside the laboratory over paved ground [73]. Hafner and Smith reported that subjects demonstrated a significant increase in outdoor SSWS without a significant change in divided attention task performance when using a swing and stance MPK compared with an NMPK [72]. Interestingly, they attributed this finding to those individuals originally considered to be limited community ambulators (i.e., MFCL-2).

In contrast to physiological measures of cognitive demand, significant differences in subject-reported cognitive demand required for ambulation have been described between prosthetic knees in the MPK literature [72–73,94]. The use of swing and stance MPKs was found to significantly reduce subjective reports of cognitive burden, as evaluated through two ad hoc outcome measures, the PCBS [94] and PEQ-A [72–73]. Items in these questionnaires addressed several key issues, including subjects' perceived concentration, mental fatigue, and ability to multitask while walking.

Table 6 shows the EESs we developed related to cognitive demand outcomes.

Table 5.

Activity empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
2-A. Use of swing and stance MPKs results in equivalent step counts, frequency of activity bouts, and activity bout duration when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [73,91]	Low
2-B. Use of swing and stance MPKs results in increased self-reported mobility when compared with use of NMPKs among individuals with unilateral TFLL.	3 × Moderate [79,89,92] 4 × Low [72–73,88,90]	Moderate

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFLL = transfemoral limb loss.

Table 6.

Cognitive demand empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
3-A. Use of swing-only or swing and stance MPKs results in equivalent ability to ambulate while performing secondary cognitive task when compared with use of NMPKs among individuals with unilateral TFLL.	1 × Moderate [94] 3 × Low [72–73,95]	Moderate
3-B. Use of swing and stance MPKs results in decreased perception of cognitive demand required for walking when compared with use of NMPKs among individuals with unilateral TFLL.	1 × Moderate [94] 2 × Low [72–73]	Moderate

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFLL = transfemoral limb loss.

Gait Mechanics

Gait mechanics outcomes are those associated with the temporal, spatial, kinematic, and/or kinetic parameters of gait. Measures of gait mechanics reported in the MPK literature include walking speed, spatial step symmetry, temporal step symmetry, kinematics, joint moment, joint power, GRF, and limb segment jerk [73,76–78,80–81,90,96–98].

Studies investigating temporal-spatial outcomes have reported significant differences between MPKs and NMPKs in one area (SSWS) and with one type of MPK (swing and stance). Three studies examined differences in SSWS on level ground as subjects used both swing and stance MPK and NMPK prostheses [78,81,90,98]. Two publications described a group of subjects ($n = 8$) that walked over an 11 m stretch of level terrain and adopted a significantly higher SSWS using a swing and stance MPK than an NMPK [81,98]. Similarly, a larger study of 19 subjects found that swing and stance MPK users walked significantly faster over 75 m level terrain than when they wore the NMPK [90]. In these studies, extended accommodation periods of 30 d [81,98] and 90 d [90] were provided to allow subjects to adjust to the different interventions. A third study of eight subjects showed no significant difference in SSWS between two different swing and stance MPKs and a single NMPK over a 0.25 mi distance [78]. In this study, subjects were provided with approximately 10 min of accommodation time for each intervention. Similarly, two studies ($n = 10$ and $n = 6$) comparing swing-only MPKs with NMPKs in a single session (i.e., no extended period of accommodation) showed no significant change in SSWS between interventions [76,80].

Neither temporal nor spatial measures of walking symmetry (i.e., step timing and step length, respectively) have been reported to consistently and significantly vary with prosthetic knee at SSWS [73,76–78,80,98]. Several studies comparing swing and stance MPKs with NMPKs have reported no significant temporal [77] or spatial [73,77,98]

differences in step symmetry at SSWS. However, Johansson et al., who compared temporal-spatial measures among two swing and stance MPKs and an NMPK with eight subjects, reported a significant increase in affected side-step time between one of the MPKs and the two other interventions [78]. This study also differed from the aforementioned studies in that subjects were accommodated for a relatively short period of time (i.e., 10 min) and walked on a treadmill during assessment. Comparisons between swing-only MPKs and NMPKs in several studies showed no significant change in spatial [80] or temporal and spatial [76,99] measures of symmetry.

Kinematic analyses of knee motion at SSWS have shown mixed and conflicting results. Three studies examined peak knee flexion during early stance, often termed “stance-phase knee flexion” [96–98]. Herr and Wilkenfeld completed an early pilot study of four subjects comparing a noncommercial swing and stance MPK with the subjects’ customary NMPKs and observed increased knee flexion during stance while using the MPK [96]. However, they performed no statistical analysis. Subsequently, a comparison between a commercially available swing and stance MPK and NMPK in eight subjects with traumatic LLL showed no significant differences in stance-phase knee-flexion angle at SSWS [98]. Conversely, a larger study of 15 subjects using the same two interventions found significantly increased knee-flexion angle during stance [97]. Segal et al. also examined peak knee flexion during swing phase and reported a significant [98] decrease in knee-flexion angle when subjects used the swing and stance MPK prosthesis compared with the NMPK. Kinematic measures for all of these studies were measured in similar environments (i.e., motion analysis laboratories) and used similar techniques.

The reviewed literature also included studies that used combined kinematic and kinetic analyses in an effort to evaluate changes produced by different knee

components. Three studies examined differences in joint moments between swing and stance MPKs and NMPKs [78,97–98]. Two studies of 8 and 15 subjects, respectively, showed a significant increase in the prosthetic side knee moment while subjects used the MPK compared with the NMPK [97–98]. In both studies, subjects were accommodated to each intervention for an extended period of time before testing. Johansson et al., in a study with a shorter accommodation period (10 min), showed no significant difference in prosthetic side knee moment in early stance; however, a significant decrease in knee moment was measured at toe-off with the MPK compared with the NMPK [78]. Out of the aforementioned studies, only Johansson et al. evaluated peak hip moment in terminal stance [78]. They reported that users showed a significantly reduced prosthetic side hip moment at terminal stance with two different swing and stance MPKs compared with the NMPK.

Two studies that examined the joint moments associated with prosthetic ambulation also investigated differences in joint powers as they relate to the use of swing and stance MPK and NMPK prostheses [78,98]. Each study evaluated eight subjects in a gait laboratory. Johansson et al., evaluating interventions within a single session, reported significant differences in prosthetic side joint powers [78]. They reported that using MPKs resulted in significantly increased knee power at toe-off, significantly increased hip power at mid-to-late stance, and significantly decreased hip power at toe-off compared with the NMPK [78]. Segal et al., however, did not find any significant differences in prosthetic-limb joint kinetics [98]. They reported joint powers in the contralateral limb, the results of which suggested that the only change between the swing and stance MPK and NMPK condition occurred at the ankle [98]. Subjects showed a significantly lower maximum ankle power when using the MPK than when they used the NMPK.

Significant differences in gait outcomes associated with use of a swing and stance MPK prosthesis, including changes in GRF and jerk of the shank and thigh, appeared in one study each. In a study of eight subjects, Segal et al. reported that using a swing and stance MPK (compared with an NMPK) was associated with significantly decreased peak GRF on both the prosthetic and contralateral sides and a significantly increased time of peak GRF on the prosthetic side [98]. In another study of eight subjects, Johansson et al. reported that using either of two types of swing and stance MPKs was associated

with significantly decreased root-mean-square jerk of the shank and thigh [78]. They reported that this indicated an improvement in the “smoothness of gait” when users walked in the MPK prosthesis.

Table 7 shows the EESs we developed related to gait mechanics outcomes.

Environmental Obstacle Negotiation

Environmental obstacle negotiation outcomes are those associated with ambulation across nonlevel surfaces, including uneven terrain, slopes, and stairs. Measures of environmental obstacle negotiation reported in the MPK literature include walking speed over uneven terrain, quality of stair descent, quality of slope descent, the Montreal Rehabilitation Performance Profile (MRPP), perceived ability to negotiate the obstacle, and performance on an obstacle course [72–73,83,88,90].

The influence of MPK technology on an individual’s ability to negotiate environmental obstacles varies across the body of literature, depending on the obstacle (i.e., uneven terrain, stairs, incline), direction (i.e., ascent or descent), and type of MPK (i.e., swing and stance or stance only). The ability to walk over uneven terrain, quantified through the subject’s time required to traverse an established obstacle course, was reported to significantly improve with the use of swing and stance MPKs [72–73,83,90]. The length of these courses varied from 12.2 [83] to 73.2 [72] m and included varying obstacle elements, including grass [72–73,90], rocks [72–73,90], sand [72–73,90], wood chips [72–73], cement [72–73], and/or carpet [83]. Datta and Howitt measured the ability to negotiate uneven terrain with swing-only MPKs through subjective reports [88]. The majority of users (14 of 22) reported that the swing-only MPK improved their ability to walk over uneven terrain; one subject reported that the swing-only MPK made negotiation more difficult.

Two different research groups measured the ability to descend stairs and inclines while using a swing and stance MPK compared with an NMPK prosthesis [72–73,90]. The influence of MPK technology on stair descent was measured with both the Stair Assessment Index (SAI) [72–73], an ad hoc observational scale, and the MRPP [90], an instrument designed to assess function in children with intellectual disability [100]. Both showed a significant improvement in the quality of stair descent gait patterns when subjects used the swing and stance MPK compared with the NMPK. Interestingly, in

Table 7.

Gait mechanics empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
4-A. Use of swing and stance MPKs results in increased SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	4 × Low [78,81,90,98]	Low
4-B. Use of swing-only MPKs results in equivalent SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [76,80]	Low
4-C. Use of swing and stance MPKs results in equivalent spatial gait symmetry (i.e., step length) at SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	3 × Low [73,77,98]	Low
4-D. Use of swing-only MPKs results in equivalent spatial gait symmetry (i.e., step length) at SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [76,80]	Low
4-E. Use of swing and stance MPKs results in equivalent temporal gait symmetry (i.e., step length) at SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [77–78]	Insufficient
4-F. Use of swing and stance MPKs results in equivalent peak stance-phase knee-flexion angle in early stance at SSWS when compared with use of NMPKs among individuals with unilateral TFLL.	1 × Moderate [97] 2 × Low [96,98]	Insufficient
4-G. Use of swing and stance MPKs results in increased prosthetic knee moment in early stance when compared with use of NMPKs among individuals with unilateral TFLL.	1 × Moderate [97] 2 × Low [78,98]	Low
4-H. Use of swing and stance MPKs results in equivalent prosthetic hip power in late stance when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [78,98]	Insufficient

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, SSWS = self-selected walking speed, TFLL = transfemoral limb loss.

an ad hoc survey of swing and stance MPK users, Jepson et al. found that three of five reported that walking down stairs was more challenging than when using an NMPK [77]. In a similar survey of swing-only MPK use, they found that 5 of 22 subjects reported that the MPK improved stair descent, while the remainder of the subjects reported no difference [88].

Hafner and Smith [72] and Hafner et al. [73] used a tool similar to the SAI, the Hill Assessment Index (HAI), to quantify the quality of hill descent gait patterns along with the time required for subjects to descend a 28.2 m decline. Hafner et al. reported a significant decrease in the time of hill descent when subjects used a swing and stance MPK compared with an NMPK [73]. A follow-up publication revealed that HAI scores and time of hill descent were significantly improved in the MPK condition for MFCL-2 subjects, while hill descent time was improved for MFCL-3 subjects [72]. In a survey comparison of swing-only MPKs and NMPKs, Datta and Howitt revealed that the majority of users (13 of 22) reported an

improved ability to negotiate slopes and hills in the MPK intervention, while one subject reported that the MPK made it more difficult [88].

Table 8 shows the EESs we developed related to environmental obstacle negotiation outcomes.

Safety

Safety outcomes are those associated with balance, balance-confidence, and the occurrence of adverse events such as stumbles or falls. Measures of safety reported in the MPK literature include the reported frequency of adverse events, subject-reported balance confidence, Activities-specific Balance Confidence (ABC) score, sensory organization test (SOT), and knee angle during gait perturbation [72–73,77,90,97,101–103].

The self-reported frequency of adverse events (i.e., stumbles and falls) has been used to quantify the differences in safety provided by MPK and NMPK interventions. In a study of 17 subjects receiving a swing and stance MPK following use of an NMPK, Hafner and

Table 8.

Environmental obstacle negotiation empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
5-A. Use of swing and stance MPKs results in increased walking speed on uneven terrain when compared with use of NMPKs among individuals with unilateral TFLL.	4 × Low [72–73,83,90]	Low
5-B. Use of swing and stance MPKs results in improved gait pattern during stair descent when compared with use of NMPKs among individuals with unilateral TFLL.	3 × Low [72–73,90]	Low

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFLL = transfemoral limb loss.

Smith showed a significant decrease in the frequency of stumbles, semicontrolled falls, and uncontrolled falls in the study population [72]. Specifically, those individuals rated at the MFCL-2 level showed a significant decrease in the frequency of uncontrolled falls. Similarly, using data from a study of 19 users, Kahle et al. reported significantly fewer stumbles and falls while using the same swing and stance MPK compared with the NMPK [90]. In a third study consisting of five subjects, Jepson et al. found that two reported more stumbles and falls after receiving the MPK but that neither subject attributed the falls to the knee “giving way” [77].

Survey questions designed to elicit responses related to confidence and frustration with respect to balance, falls, and knee performance were also reported in the literature [72–73,101,103]. Comparison between a swing and stance MPK and NMPKs in a group of 17 subjects found a significantly reduced self-reported frustration with falls [72–73] and significantly higher confidence [72] when subjects used the MPK. Further, Hafner and Smith found significantly increased confidence in a smaller (i.e., $n = 9$) MFCL-3 cohort [72]. Berry et al., in an ad hoc survey of 368 MFCL-3 individuals who had been prescribed a

swing and stance MPK, found that users had significantly higher confidence in their MPK compared with the previous NMPK [101]. Lastly, in a case study of a 30 yr old with traumatic amputation, Stevens and Carson found increased ABC scores after transitioning from an NMPK to a swing and stance MPK [103].

Changes in stability as a result of prosthetic knee have been investigated under static and dynamic conditions in the MPK literature. Kaufman et al. measured static balance, assessed by the SOT [104], in 15 subjects sequentially accommodated to an NMPK and then to a swing and stance MPK [97]. Tests conducted while subjects used the MPK produced significantly higher (i.e., better) individual and composite SOT scores. Blumentritt et al. assessed dynamic balance by measuring knee angle during simulated gait disruptions in a pilot study of three experienced individuals with amputation using two different types of NMPKs and a swing and stance MPK [102]. They observed a decreased knee-flexion angle in the MPK compared with the NMPK. They suggested that this was indicative of improved balance in the MPK condition.

Table 9 shows the EESs we developed related to safety outcomes.

Table 9.

Safety empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
6-A. Use of swing and stance MPKs results in decreased number of subject-reported stumbles and falls when compared with use of NMPKs among individuals with unilateral TFLL.	4 × Low [72–73,77,90]	Low
6-B. Use of swing and stance MPKs results in decreased subject-reported frustration with falling when compared with use of NMPKs among individuals with unilateral TFLL.	2 × Low [72–73]	Insufficient
6-C. Use of swing and stance MPKs results in increased subject-reported confidence while walking when compared with use of NMPKs among individuals with unilateral TFLL.	1 × Moderate [101] 3 × Low [72–73,103]	Moderate

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFLL = transfemoral limb loss.

Preference and Satisfaction

Preference and satisfaction outcomes are those associated with a user's selection of or preference for a prosthetic knee as well as his or her overall contentment with the intervention. Measures of preference and satisfaction reported in the MPK literature include intervention selection and subject-reported satisfaction [72–73,77,80–81,88,90].

Reports of preference and satisfaction in the MPK literature indicate that subjects favor swing-only and swing and stance MPK devices over the NMPK interventions with which they were compared. Two studies allowed subjects to choose their intervention of choice following the test protocol. As few as 74 [90] and as many as 82 [73] percent of subjects selected a swing and stance MPK over an NMPK. In these studies, the MPK was the most recently worn intervention. However, an unknown percentage of subjects in a randomized trial also provided unsolicited preference for a swing and stance MPK compared with a swing and stance NMPK [81]. Note that the assessment of preference was universally performed immediately following testing. In a 6 mo follow-up, Jepson et al. showed that three of five individuals who had been provided with a swing and stance MPK in the study were no longer using that intervention [77]. No other long-term follow-ups of preference were conducted.

Reports of preference related to swing-only MPKs compared with NMPKs were less common but reported similar findings. In a retrospective assessment of preference by swing-only MPK users, Kirker et al. showed that significantly more individuals preferred the MPK they were currently using to their previously used NMPK [80]. In a prospective trial of swing-only NMPK users that were switched to swing-only MPKs, Datta and Howitt reported that 1 of 22 users would happily wear his or her NMPK device again after using the MPK [88].

Subject-reported satisfaction was similarly reported to be related to prosthetic knee type. Two studies noted the results of the first question of the PEQ [50], which asks the subject, "Over the past 4 wk, how happy have you been with your prosthesis?" [73,90] This question has not been independently validated as a stand-alone tool [50]. In both studies, the swing and stance MPK was found to score significantly higher (i.e., better) in satisfaction than the NMPK [73,90].

Table 10 shows the EESs we developed related to preference and satisfaction outcomes.

Economics

Economic outcomes are those associated with the financial expense or cost-effectiveness of the intervention. Measures of economic outcomes reported in the MPK literature include prosthesis acquisition costs, total social costs, and incremental cost-effectiveness ratios [89,92,105].

Economic analyses of MPK and NMPK technology in the published literature, conducted primarily in Europe, have reported the costs associated with procuring and using different types of prosthetic knees [89,92,105]. Costs associated with the acquisition of the prosthesis (in euros (€)) are a common element among three studies conducted in Italy [89], the Netherlands [92], and Sweden [105] and were derived from either national cost estimates [92] or patient and practitioner interviews [89,105]. Mean acquisition costs of a swing and stance MPK ranged from €17,003 (\$21,834) [105] to €19,270 (\$26,012) [92], while mean acquisition costs of NMPKs spanned €3,600 (\$4,328) [89] to €8,057 (\$10,876) [92]. Differences in acquisition costs were reported to be significantly different between the prosthetic knees [89,92].

Table 10.

Preference and satisfaction empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
7-A. Use of swing and stance MPKs results in increased subject-reported preference when compared with use of NMPKs among individuals with unilateral TFL.	4 × Low [73,77,81,90]	Low
7-B. Use of swing-only MPKs results in increased subject-reported preference when compared with use of NMPKs among individuals with unilateral TFL.	2 × Low [80,88]	Low
7-C. Use of swing and stance MPKs results in increased subject-reported satisfaction when compared with use of NMPKs among individuals with unilateral TFL.	2 × Low [73,90]	Low

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFL = transfemoral limb loss.

Two studies considered the overall social costs associated with the prosthesis [89,92]. This includes the costs of acquisition, inpatient care, outpatient care, hospital, housekeeping, transportation, adaptive technology, and loss of productivity. Annualized social costs for the MPK ranged from €13,334 (\$16,032) [89] to €14,006 (\$18,906) [92] and €12,917 (\$15,531) [92] to €13,384 (\$16,092) [89] for the NMPK. These differences in costs were not found to significantly differ between the MPK and NMPK [89,92].

Two studies reported incremental cost-effectiveness ratios (€/quality adjusted life year [QALY]) comparing swing and stance MPKs with NMPKs [89,105]. Estimates for the cost (€) per QALY associated with the use of a swing and stance MPK compared with an NMPK varied between €3,218 (\$4,132) [105] and €35,971 (\$43,251) [89] depending on the cost of the NMPK.

Table 11 shows the EESs we developed related to economic outcomes.

Health and Quality of Life

Health and QOL outcomes are those associated with a user's overall health and perceived general well-being. Measures of health and QOL reported in the MPK literature include the SF-36 general health subscale, PEQ well-being subscale, and QALYs [72–73,79,92,105].

Outcomes related to general health were reported to differ based on the type of measure used to evaluate the construct of health. Two studies that reported the SF-36 general health subscale found increased scores (i.e., improved health) when using a swing and stance MPK compared with the NMPK, but these findings were not significant [73,92]. Three studies that reported health using the PEQ well-being subscale similarly found increased (i.e., improved well-being) scores associated with use of a swing and stance MPK after wearing an NMPK [72–73,79]. Two of the studies reported this difference between interventions as significant [72,79].

Health effectiveness of the prosthetic interventions was also determined through the EuroQol EQ-5D [106]. Two studies computed QALY from the EQ-5D utility weights for each intervention [89,105]. The QALY ranged from 3.55 [89] to 5.98 [105] for the MPK and 3.13 [89] to 3.60 [105] for the NMPK. Gerzeli et al. found a significant difference in QALY between the MPK and NMPK [89]. The health effectiveness measures obtained in these studies were used to compute incremental cost-effectiveness ratios, values intended to be used by healthcare agencies to determine provision decisions.

Table 12 shows the EESs we developed related to health and QOL outcomes.

Table 11.

Economic empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
9-A. Prescription of swing and stance MPKs results in increased prosthesis acquisition costs compared with NMPKs among individuals with unilateral TFLL.	2 × Moderate [89,92] 1 × Low [105]	Moderate
9-B. Prescription of swing and stance MPKs results in equivalent total costs of prosthetic rehabilitation compared with NMPKs among individuals with unilateral TFLL.	2 × Moderate [89,92]	Moderate

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, TFLL = transfemoral limb loss.

Table 12.

Health and quality of life empirical evidence statements (EESs).

EES	Supporting Study	Level of Evidence
8-A. Use of swing and stance MPKs results in equivalent self-reported general health compared with NMPKs among individuals with unilateral TFLL.	1 × Moderate [92] 1 × Low [73]	Moderate
8-B. Use of swing and stance MPKs results in increased self-reported well-being compared with NMPKs among individuals with unilateral TFLL.	1 × Moderate [79] 2 × Low [72–73]	Moderate
8-C. Use of swing and stance MPKs results in increased QALY compared with NMPKs among individuals with unilateral TFLL.	1 × Moderate [89] 1 × Low [105]	Moderate

MPK = microprocessor-controlled prosthetic knee, NMPK = non-microprocessor-controlled prosthetic knee, QALY = quality adjusted life year, TFLL = transfemoral limb loss.

DISCUSSION

Systematic reviews are widely recognized as one of the highest forms of evidence and a valuable component of EBP [67,107]. The methodical approach to the collection, evaluation, and synthesis of a body of literature inherent to a systematic review provides the means to address a focused and relevant clinical question. Here, that question was, Does the prescription, fit, and use of MPKs lead to changes in outcomes for individuals with unilateral TFL when compared with NMPKs? Thus, the goal of this review was to systematically identify, assess, and interpret the body of scientific literature that compares MPK and NMPK and to synthesize the knowledge obtained through that process into clinically useful empirical evidence. Further, we hoped that such evidence could be used to develop clinical guidelines, establish research priorities, inform healthcare policy, and advance knowledge related to O&P research [71].

The identification and collection process produced 27 peer-reviewed scientific publications that met the selection criteria and were included in this review. While this is fewer than the number of publications ($n = 240$) included in one recent systematic review of O&P outcomes [108], it is consistent with the number of publications ($n = 25\text{--}34$) that have appeared in others performed using similar strategies [109–112]. The number of publications included in this review is also similar to a 2004 Cochrane Review of prosthetic feet that included 29 total publications [113–114].

As previously noted, the population of study across the reviewed body of literature was predominantly individuals with an amputation due to nondysvascular etiologies (trauma, tumor, osteomyelitis, congenital, or other). This contrasts sharply with the general population with amputation, wherein the most common (>80%) cause of LLL is vascular disease [1–2]. While this may limit the generalizability of the evidence obtained in this review to a portion of the overall population with amputation, note that patients with amputation with vascular causes are not commonly fit with MPKs [62]. Perhaps of greater effect of the clinical relevance of this review is the mobility level of included subjects. Historically, MPKs have been prescribed for MFCL-3 or -4 and select MFCL-2 patients with the “cardiovascular reserve, strength, and balance to use the prosthesis” [62]. The subjects described in those studies reviewed here all fall into one of these classifications. Thus, the outcomes presented in the review likely

represent those that may be achieved by individuals most commonly fit with MPKs. Readers are further advised to review the demographics of the individual studies (**Table 3**) reflected in each EES when extrapolating the findings to a specific patient or patient population.

We specified the intervention of focus in this review to be MPKs. However, it should be acknowledged that the reviewed body of literature included several different types and several different models of MPKs. As noted previously, both swing-only and swing and stance MPKs were studied in the reviewed literature. We discovered four commercially available models of MPKs studied within this body of literature. These included the Compact C-Leg, SmartIP, RHEO KNEE, and Adaptive Knee (Endolite; Miamisburg, Ohio). Although we found the C-leg and the SmartIP to be the focus of multiple studies (i.e., 17 and 6, respectively), the RHEO KNEE and Adaptive Knee (in their commercialized forms) were studied once each.

The large number of outcome measures (i.e., more than 45 unique measures in 9 outcome areas) described in the reviewed publications was indicative of the breadth of the reviewed literature. While this diversity contributed to a greater number of EESs, the heterogeneity of outcome measures used across the studies also reduced the level of evidence available to support the derived EESs. We considered the absence of homogenous use of outcome measures across this body of literature to be one of the primary reasons that the evidence was not stronger than that presented here. However, identification of these outcome topics and the associated measures offers the potential for other investigators to contribute greatly to the overall evidence in this area by augmenting the reviewed findings with additional research.

Empirical Evidence Statements

The following sections discuss the findings of the systematic review and the derived EESs within the context of existing literature related to the outcome topics.

Metabolic Energy Expenditure

Despite similar metabolic energy requirements as individuals without amputation in static standing [30], the ambulation of individuals with TFL is 27 to 89 percent less efficient than nondisabled controls [30,32,115–117]. This difference has been attributed to excessive muscular cocontraction, atypical trunk motion, and/or compensatory limb movements [115]. Due to the significantly increased

metabolic cost required for prosthetic ambulation, lower-limb prosthetic interventions are often designed to mitigate these costs. For example, an MPK is intended to constantly adjust the knee-joint resistance in order to accommodate a wider range of walking speeds and facilitate a more efficient gait [62]. Theoretically, this should reduce the energy required by the user to accelerate and decelerate the limb during swing phase. Similarly, a swing and stance MPK should help stabilize the user during single-limb stance, thus reducing the usual energy required for the muscular cocontractions and/or accessory bodily movements needed to maintain balance. Given that most prostheses are “tuned” by the prosthetist for the patient’s SSWS, an MPK might be expected to reduce metabolic energy expenditure most when he or she walks at speeds above or below the SSWS. However, the available peer-reviewed literature indicates that O_2 cost is equivalent between swing and stance MPKs and NMPKs across a range of walking speeds (EES 1-A).

One type of MPK (swing and stance) was found to reduce metabolic energy expenditure through a decrease in O_2 rate at SSWS (EES 1-B). However, the studies that contributed to this finding [78,82–83] all shared a common trait: a relatively short period of accommodation to the prosthetic interventions (no more than a few minutes). Thus, it appears that when little or no accommodation time was provided to subjects prior to testing, small but significant differences in O_2 cost [83] and rate [78,82–83] emerged. However, when longer periods of accommodation were provided, significant differences in measures of metabolic energy expenditure did not appear [79,81]. While this theme did not extend to studies of swing-only MPKs, it is one worth additional exploration.

Comparisons among studies of metabolic energy expenditure were complicated by the variety of outcome measures used by study investigators. Six studies assessed O_2 rate, which measures the level of physical effort required to perform an activity over a period of time [33]. Four other studies [76,79,81,83] reported results in terms of O_2 cost, which describes the amount of energy used to perform the task of walking over an assigned distance [33]. O_2 cost is generally preferred as a measure of gait efficiency because it accounts for walking speed, while O_2 rate does not. This may be an important factor to consider because research suggests that individuals with LLL decrease their walking speed to maintain an O_2 rate that is equal to that of individuals without amputation [117]. Therefore, measuring O_2 rate

without considering O_2 cost and SSWS may be misleading. Orendurff et al. elected to use the net O_2 cost, which extracts the resting O_2 cost from that associated with the activity [81]. This may be important because resting O_2 cost is a noted contributor to gross O_2 consumption during ambulation [118] but is not expected to be affected by a prosthetic intervention. Thus, removing resting O_2 cost from the analysis may allow subtle changes in metabolic energy expenditure resulting from use of a component to be more easily detected.

Note that the significant differences in metabolic energy expenditure reported in this body of literature in most cases exceeded the 3 to 5 percent normal variation of O_2 consumed during submaximal exercise in nondisabled individuals [119]. Because Buckley et al. suggested that such changes are clinically relevant [75], the changes produced by the swing and stance MPK may be interpreted to be both clinically and statistically significant.

The majority of the reviewed metabolic energy expenditure studies incorporated treadmill ambulation tests [75–76,79,80,82–84], but several used overground ambulation tests [77,78,81]. While no clear pattern in the results emerged between those using treadmill versus overground ambulation, it has been established that the metabolic costs for treadmill ambulation are greater than overground walking among nondisabled individuals [120], patients with stroke [121], and individuals with TFL [122]. Thus, take caution when directly comparing the results of treadmill and overground ambulation tests.

One important consideration in the collection and interpretation of metabolic energy expenditure data is the ecological validity of the experiment. Most measures of O_2 uptake (i.e., those using standard gas oximetry techniques) require prolonged ambulation in order to reach a steady state. Once it is achieved, activity must be maintained for a period of time to allow for adequate sampling of the expired gases. The studies included in this review reported testing times that ranged from 3 to 16 min. Interestingly, the usual activity bout duration among individuals with TFL has been reported to be between 1 and 2 min consisting of 17 to 34 steps [91]. Thus, while metabolic experiments in this body of literature may assess the physiological capacity of individuals with TFL, they are often conducted under atypical conditions that may not well reflect how the prosthesis is used by representative individuals. Kaufman et al. described an alternative approach to address this mismatch between test environment and real world conditions [79]. In this study, investigators used a DLW technique [85] to

estimate TDEE in the prosthesis users' free-living environment. This technique has been used across a wide range of populations and is considered to be a criterion measure of physical activity [123]. While Kaufman et al. reported that TDEE was equivalent between swing and stance MPKs and NMPKs, PAEE increased with the use of swing and stance MPKs, leading to the conclusion that the amount of activity in which those subjects engaged increased with that intervention [79]. Although further work is needed to replicate and validate these findings, this appears to be a promising technique to complement or address the ecological limitation of laboratory-based metabolic energy expenditure testing.

Another alternative to traditional, physiological measures of metabolic energy expenditure are PROs. Kaufman et al. reported that using a swing and stance MPK was associated with a decreased RPE when compared with using an NMPK [79]. While such findings from a single study may not contribute to the formulation of an EES in this review, the knowledge that RPE decreased [79] and other physiological measures of metabolic energy expenditure did not change after longer periods of accommodation [79,81] may indicate that traditional measures are not sensitive enough to capture the differences subjects perceived between MPKs and NMPKs. Recently renewed interest in other means to assess metabolic energy expenditure, such as dynamic walking theory [124–125], may also provide insight and unique methodologies to further evaluate metabolic energy expenditure among individuals with TFLL and the effect of select componentry.

Lastly, as the number of commercially available MPKs increases, clinicians will have to decide not only between MPKs and NMPKs but also among the variety of MPKs available. While not informing directly upon the primary question of interest in this review, Chin et al. found no statistically significant difference in O_2 rate between a swing and stance MPK and a swing-only MPK across a range of walking speeds [126]. Similarly, subjects' most efficient walking speed was equivalent between the two knees [126]. Johansson et al. also reported no significant difference in O_2 rate between two different swing and stance MPKs [78]. Thus, while it appears that different types of MPKs may not change metabolic energy expenditure, more research is needed to confirm this finding.

Activity

As noted previously, there are many physical impairments associated with TFLL. These impairments are often so severe that only 50 to 72 percent of individuals with TFLL are reported to achieve ambulation with a prosthesis [6,8,14,127]. Those that do may require an additional walking aid (i.e., canes or crutches), particularly for functioning outside of the home environment [6,8,128–129]. While eight studies identified in this review included assessments of activity (**Table 3**), they were all published within the last 3 yr (2006–2009), perhaps indicating an elevated interest in assessing outcomes in this area.

Ambulatory individuals with TFLL have been found to take anywhere from 1,069 [41] to 2,675 [91] steps/d. This is greater than the minimum of 600 steps/d thought to be necessary to sustain an independent lifestyle in a single-level residence with moderate family or social support and in some cases above the 1,100 to 1,450 steps/d recommended for independent living [40]. This is well below the average number of steps reported for both “highly active” and “moderately active” older community-dwelling adults (i.e., 12,660 and 7,596 steps/d, respectively) and even below those classified as “inactive” (i.e., 3,893 steps/d) [130]. Further, it has been reported that steps taken by individuals with TFLL appear as very short bouts lasting 1 to 2 min and consisting of ≤ 17 steps [91]. This is consistent with reports that most (75%) individuals with TFLL walk < 0.5 km/d and 16 percent walk > 2 km/d [128]. What is relatively unknown is how different prosthetic interventions, such as prosthetic knees, influence this type of activity.

The evidence reviewed suggests that activity measures such as step count, activity bout duration, and the frequency of activity bouts, which represent the amount of activity performed, do not appear to significantly differ by prosthetic knee type (EES 2-A). Though contrary to several investigators' hypotheses [73,91], it would appear that the use of a swing and stance MPK does not increase the amount or frequency of activity that is performed. The most straightforward explanation is that individuals with TFLL, like anyone else, have a basic amount of ambulatory activity (i.e., moving around the house, going to work, going to the store) that they conduct on a normal basis and that a change in the prosthesis does not encourage them to change the amount or frequency of their daily patterns. Logically, a change in the volume of activity would result if the prosthetic component addressed some

functional limitation that prevented individuals from engaging in a desired activity that required a greater number of steps to perform. The subjects of these activity studies were established individuals with amputation, and may have adapted their lives (and activity patterns) to meet their needs. Therefore, use of a swing and stance MPK may not have produced the hypothesized change in volume of activity.

Conversely, it might be argued that while the volume of activity may not change as the result of a prosthetic intervention, the type of activity or the ease with which activity is performed may change. With the added stance-phase stability afforded by swing and stance MPKs, subjects may be more likely to engage in activities that they had previously not felt safe or confident performing. This would not necessarily be reflected by an increase in the amount or frequency of activity as assessed through measures of step counts but would indicate a relevant clinical change in activity. This change in type of activity performed or the ease with which it is performed may be reflected in EES 2-B, which describes an increased patient-reported mobility with the use of a swing and stance MPK. Many of the questions in the contributing questionnaires asked about types of activities performed or the ease with which they were performed rather than how much activity was performed. Therefore, it may be that the use of a swing and stance MPK is more likely to increase the ease with which activity is performed or change the types of activities that are performed rather than the amount.

Another way that a change in activity may be measured is through the MFCL, the practitioner's assessment of an individual's ability or potential to ambulate. Several publications in this reviewed body of literature suggested that the use of swing and stance MPKs may increase the MFCL among MFCL-2 and -3 patients when compared with the use of NMPKs [72,90]. Kahle et al. found that four of nine study subjects, originally evaluated as MFCL-2, were re-evaluated as MFCL-3 upon conclusion of the trial [90]. Hafner and Smith similarly found that four of eight MFCL-2 subjects improved to MFCL-3, while three of nine MFCL-3 subjects improved to MFCL-4 [72]. The relevance of these findings is that subjects who were previously considered unable to traverse more than low-level environmental barriers (MFCL-2) were able to achieve unlimited community ambulation and could walk with variable cadence (both MFCL-3 traits) after exposure to the MPK. Although the causal connection between MPK

use and MFCL change was not demonstrated in these studies, these observations are nonetheless interesting.

The prospect that technology may provide the means to alter less-functional users' ambulatory potential challenges certain clinical and reimbursement paradigms. Historically, the lower a patient's ambulatory potential, the simpler and less expensive the provided prosthesis [131]. More complex and more expensive prosthetic technology has been typically reserved for the most active individuals [55]. The results reported by Kahle et al. [90] and Hafner and Smith [72] would appear to challenge this standard. For example, one commonly cited requirement for the prescription of (and reimbursement for) an MPK is that the patient demonstrates the ability to walk with a variable cadence. If not, the patient is assigned to MFCL-2 and is typically not considered eligible for an MPK. However, the preliminary results by Kahle et al. [90] and Hafner and Smith [72] may suggest that it is the use of the MPK that allows select patients to achieve variable cadence. Thus, these patients may be denied access to the very technology that may allow them to qualify for it. Though it is premature to suggest that this paradox exists based on the existing evidence, these findings merit further investigation.

Another possible explanation for the evidence not showing the hypothesized change in step activity with the different types of prosthetic knees may be related to the period of monitoring. Selecting an appropriate step count sampling interval is needed to represent an individual's true activity and reliably extrapolate beyond the period of measurement. Tudor-Locke et al. [132] reported that 3 d worth of data collection were sufficient to provide a reliable estimate of weekly step counts, while 7 d are recommended in order to establish a reliable estimate of monthly activity [133]. For an accurate estimation of annual step counts, Kang et al. recommended a minimum of 30 d of continuous monitoring or 14 d of random monitoring [134]. Interestingly, Togo et al. stated that annual step counts can be estimated with as few as 8 d, provided that they are acquired with random and seasonal sampling; otherwise, they recommended up to 105 d of consecutive observations [135]. The two studies of prosthetic knees relevant to the EES developed in this review collected continuous step data for 1 [91] and 2 [73] wk periods, respectively. Thus, while consistent with recommendations by the device manufacturer [93], these results should be considered reasonable estimates of monthly activity. One area of future study may be to examine

longer sampling periods to see whether the results reported in the literature are confirmed over longer time intervals.

Although readers may question the logic of presenting several alternative hypotheses regarding these activity outcomes, one reason for such considerations is the presence of contradictory self-reported evidence related to this outcome topic. For individuals with LLL, the most impaired factor of HRQL is reported to be physical function or mobility [136–138]. Notably, this review discovered that one of the most commonly reported outcomes associated with use of an MPK (compared with an NMPK) was an increase in self-reported mobility (EES 2-B). This finding creates an interesting dichotomy between physiological or biomechanical tests and self-reported outcomes. Perhaps most importantly, it stresses the importance of and need for including both types of measures when evaluating outcomes involving subjects. Doing so may reveal subtle differences in perspective, stimulate new directions of scientific inquiry, and encourage the use of new methodological approaches. Such approaches to studying activity level might include methods like PowerLine Positioning [139], neural network recognition of motor activity classes [140], and nonlinear analysis techniques [141].

Cognitive Demand

Walking is generally regarded as an activity that requires minimal attention [142–143]. However, ambulation with a transfemoral prosthesis may necessitate greater concentration due to the loss of traditional peripheral sensorimotor structures in the lower limb, an increased reliance on visual information for afferent input [29,46], and the need to focus on stabilizing the prosthetic knee with the remaining proximal musculature [29,46]. Further, the elevated cognitive burden associated with ambulation in non-disabled individuals over differing terrain conditions [144] or during the performance of concurrent, unrelated cognitive tasks [145] is likely to be as much or more of a concern to individuals with LLL. The addition of MPC to a prosthetic knee is often assumed to decrease the cognitive attention required for ambulation [146]. However, the current empirical evidence, as established through this systematic review, indicates that this assertion is substantiated by PROs of perceived cognitive demand (EES 3-B) and is not yet well established through physiological or biomechanical measures of cognitive demand (EES 3-A).

One reason for the inconsistency in these findings may be due to the challenges associated with objectively measuring cognitive demand. Research studying the cognitive (sometimes referred to as “attentional”) demands associated with an activity frequently use a dual task-paradigm where the primary task (ambulation) is performed concurrently with a secondary task (e.g., answering questions) of some mental difficulty [147]. The extent to which performance on the primary and/or secondary tasks degrades when performed together is then used as a measure of cognitive demand. One challenging element in conducting experiments of this nature is in the selection of a concurrent, secondary task that is sufficiently difficult so as to interfere with the automaticity of the primary task. Further, the experimental control of the primary and secondary tasks should be managed to provide an assessment of either the difficulty in conducting one or more cognitive tasks while simultaneously conducting a performance task (goal 1) or evaluation of the change in primary task performance caused by introducing one or more secondary tasks (goal 2). To measure the former, the performance task should be kept constant (e.g., requiring subjects to walk at a constant speed for all conditions) while the cognitive tasks of varying difficulty are applied. The results of the cognitive tests (when compared with results obtained when subjects are not performing the primary task) may then be used to assess the additional cognitive demand required to conduct the primary task. To measure the latter, the performance of the primary task is allowed to change (e.g., subjects are allowed to vary their walking speed) and controlled secondary cognitive tasks are applied to examine the influence of distraction on the primary task. The addition of different interventions, such as the MPK and NMPK prostheses, increases the complexity of the testing, and care must be taken to properly control the experimental conditions.

Of those studies that included primary and secondary tasks, Heller et al. [95] and Williams et al. [94] selected an experimental design similar to that noted previously by goal 1. Both controlled the performance task (walking speed) while assessing the outcomes of a variety of secondary tasks (e.g., response accuracy and/or body sway). Neither group reported significant differences between interventions (i.e., MPK or NMPK), but Williams et al. suggested that the primary and secondary tasks selected may not have been of sufficient difficulty to challenge the subjects [94]. They suggested that the potential benefits provided by swing and stance MPKs may become detectable under more

challenging primary task conditions such as negotiating environmental obstacles. Similarly, they proposed that more difficult secondary cognitive tests could be selected to challenge the subjects. As previously noted, the selection of these tasks may be a challenge because we are unaware of published guidelines or recommendations to assist investigators in this process. However, considerations may include the type of resources used to address the task (e.g., memory, visuospatial, and/or executive function), task difficulty (e.g., a 7-digit vs 3-digit reverse numbers test), the capabilities of the subjects (e.g., individuals with dysvascular amputations may have cognitive impairments that influence task performance), and environmental factors (e.g., low-light conditions may make walking more difficult).

In contrast to Williams et al. [94], Hafner et al. [73] described an experimental design similar to goal 2 described previously. In this study, they evaluated a prosthesis user's primary task performance, as measured by time and distance, while the user performed a secondary mental loading task (i.e., reverse numbers test). Subjects were allowed to vary either or both the primary and secondary tasks. Such a situation introduces a challenge when interpreting the relative changes in performance. For example, how does one compare the results of two subjects, one who walks farther with more errors and one who travels a shorter distance with fewer errors? The first might not be as distracted by the cognitive test as the second, so a comparison of the distance traveled may not be appropriate. Given that each individual may prioritize the primary and secondary tasks differently, understanding a population result is challenging. A similar example was found in an abstract by Meier et al., wherein obstacle course time with and without a mental loading task (serial subtraction) was assessed for different knee-joint conditions (i.e., MPK and two NMPKs) [148]. While the time did not differ significantly between the MPK and NMPK conditions, the test accuracy was not reported and so the combined effect of the primary and secondary tasks was unknown. In future studies, it may be beneficial to group subjects by relative accuracy on the cognitive test scores so that comparisons are appropriately made among subjects who were attentively challenged to the same degree.

Properly managing groups in cognitive demand research may also be important for other reasons. Hafner and Smith reported that MFCL-2 subjects demonstrated a significant increase in outdoor SSWS without a significant decrease in performance on the divided attention

task while using a swing and stance MPK compared with an NMPK [72]. However, studied MFCL-3 subjects showed equivalent speed and accuracy under both prosthetic knee conditions. This finding suggests that the influence of MPKs on locomotor performance may vary based on specific individual characteristics, such as MFCL. Although further study is warranted to confirm this finding, it may again suggest that technological advances in prosthetics, such as knee MPC, may be beneficial for patients not previously considered to be ideal candidates for that technology under typical prescription criteria.

The study of cognitive demand and MP technology may also require other study design considerations. The attentional requirements of walking have been reported to vary within a gait cycle in both individuals with LLL [47] and without amputation [149]. As noted previously, MPC in an MPK is active during select phases of the gait cycle and varies with each specific model. As such, analysis of in-phase attentional demand may reveal differences among prosthetic knees that are "washed out" when the entire gait cycle is evaluated. Note that all four cognitive demand studies included in this review used tests designed to measure cognitive demand across multiple gait cycles and did not focus on specific phases. Future research designs may consider assessment of cognitive demand within the gait cycle. Such designs would require the use of reaction-time methodologies rather than those that measure the number of errors or answers that can be provided over an extended testing protocol. Such techniques may better inform how MPKs differ when the MP is active during the swing and/or stance phases of gait.

An additional consideration for future cognitive demand research may be the inclusion of a single-task condition in addition to the dual-task condition. In the single-task condition, the secondary task is performed on its own (i.e., in a seated or standing position), ideally with a high degree of proficiency. This establishes a baseline condition for the secondary task that allows for a relative assessment of its degradation after transitioning to the dual-task condition. This is similar to establishing and removing the basal metabolic rate prior to analyzing metabolic energy data and may allow for a more detailed analysis of the difficulty and hence interference caused by the secondary task during dual-task testing.

Lastly, the instructions provided to study subjects may guide or influence their attentional focus and subsequently their measured performance in the primary or secondary

tasks. For example, subjects may prioritize tasks differently if told to “walk as quickly as possible” than when told to “try to answer questions as quickly as possible.” It is likely that, if provided the former instructions, subjects would prioritize the primary task, and if provided the latter, prioritize the secondary task. Unfortunately, none of the reviewed studies referenced the explicit instructions provided to study subjects; therefore, the relative prioritization is unknown. In the future, investigators may wish to include such information to allow readers to better understand subjects’ potential for selectively allocating cognitive resources.

Gait Mechanics

In addition to increased metabolic energy expenditure, LLL has been well documented to be associated with reduced SSWS [150]. As with metabolic limitations, this deficit worsens at more proximal levels of amputation [30,33,151]. However, it is often hypothesized that modern prosthetic interventions (e.g., MPKs) have the potential to address the physical challenges associated with LLL and therefore increase a user’s SSWS compared with NMPKs. However, the evidence obtained from this review suggests that specific types (i.e., swing and stance) of MPKs have shown such potential (EES 4-A). In contrast, users appear to select similar SSWS when wearing either swing-only MPKs or NMPKs (EES 4-B). Thus, MPC of stance phase may be related to the reported changes in SSWS. One possible explanation may be that individuals with TFL choose to walk at a slower SSWS to avoid falling and that the improved safety and self-reported confidence associated with stance MPC (i.e., EESs 6-A and 6-C) may allow users to walk more rapidly.

The measurement of temporal, spatial, kinetic, and kinematic symmetry among individuals with unilateral TFL is a common scientific and clinical pursuit. These efforts are likely related to the goal of better understanding and addressing the documented asymmetry in gait parameters in this population [4,36–37,115,117,152–153] and the elevated incidence of lower-back pain [16,154–155], joint pain [16,155], and osteoarthritis [16,18,155–156] that these asymmetries are believed to cause. Prosthetic interventions such as MPKs are often evaluated for their potential to reduce asymmetry and, presumably, to affect these degenerative changes. Neither swing-only nor swing and stance MPKs were found to significantly change spatial symmetry (i.e., step length) compared

with NMPKs (EESs 4-C and 4-D). One explanation may be that spatial asymmetries are most often caused by issues that are addressed by the prosthetist while the subject walks at SSWS in the clinic. Thus, significant differences in symmetry as a result of changing prosthetic knees may appear at faster or slower walking speeds, as noted by Jepson et al. [77] and Kirker et al. [80] for swing and stance and swing-only MPKs, respectively.

Temporal symmetry (i.e., percent stance time) was not often explored, and studies reported conflicting results related to changes produced as the result of swing and stance MPK use (EES 4-E). Jepson et al. [77] reported no change in stance time between swing and stance MPKs and NMPKs, while Johansson et al. [78] reported a significantly increased step time on the prosthetic side, with one (RHEO KNEE) of the two MPK models studied [78]. Although this finding is interesting, further investigation will be required to determine whether this specific type of MPK has the potential to address temporal asymmetries. Two studies [76,99] that examined temporal symmetry between swing-only MPKs and NMPKs showed no significant differences between the prosthetic knees at SSWS [76] and CWS [99], suggesting that swing-only prosthetic knees do not greatly affect temporal symmetry.

The influence of MP technology on gait kinematics has received relatively little attention in the reviewed body of literature. The sole EES generated in this review on this topic indicated that peak stance-phase knee flexion was equivalent between swing and stance MPKs and NMPKs (EES 4-F). An increase in flexion was expected, because some models of MPKs are believed to possess so-called “stance flexion,” which presumably would allow the prosthetic knee to flex slightly during loading response. This EES (EES 4-F) was not well supported by the literature because the results varied between studies. While Kaufman et al. [97] reported significantly increased knee flexion with a swing and stance MPK compared with an NMPK, Segal et al. [98] reported no significant difference for the same comparison. A pilot study by Herr and Wilkenfeld also noted an increase in early stance flexion with the MPK but did not conduct a statistical analysis [96]. Given these conflicting results, more research is needed to draw a definitive conclusion. One potential reason that the early flexion was not measured across all the studies may be because of the alignment of the MPK. Willingham et al. suggested that MPKs may be aligned following traditional methods with the GRF too anterior to the knee-joint center, thus limiting

their ability to achieve this stance flexion [157]. Additional research would be needed to explore this hypothesis. Individual studies showed significant changes in peak swing-phase knee-flexion angle [98] and stance-phase hip angle [78] on the prosthetic limb while using swing and stance MPKs, but corroborative studies would be required to formulate EESs based on these findings.

As with joint kinematics, joint kinetics were infrequently studied across the reviewed literature. The limited kinetic evidence suggests that, in most respects, MPKs and NMPKs performed similarly. However, swing and stance MPKs were reported to significantly increase the knee-flexion moment (EES 4-G), perhaps as a result of the induced knee flexion noted in several of the studies discussed previously. Alternatively, the increased moment in this phase of gait may be due to the more anterior alignment recommended for this type of MPK compared with the traditional alignment of NMPKs. Although prosthetic hip power during late stance was found to be equivalent between knees (EES 4-H), inconsistency in the results suggests that more research is needed to strengthen the EES. While it may be expected that a more accommodating prosthetic knee might be easier to flex in late stance, reducing the need for hip flexion to enter swing phase, users with a short accommodation period showed a significant reduction in hip power with the MPK [78]. Users with 3 mo of experience did not show a significant difference in hip power between prosthetic knees, suggesting that accommodation to the knee may mitigate changes in hip power in late stance [98].

Interestingly, time since amputation and experience with the interventions varied greatly among gait mechanics studies (**Table 3**). Variations in these personal factors may affect the extent to which the subjects could learn to use and/or trust the MPK or to adopt a revised gait pattern. Similarly, the training provided to subjects was not commonly discussed. Training has been reported to have immediate and lasting effects on gait mechanics and may therefore influence outcomes when provided in conjunction with a prosthetic intervention [158]. More research is needed to understand the interaction and potential benefits of providing prosthetic interventions with physical therapy.

Evaluating gait mechanics publications also identified several methodological issues that may influence the presented outcomes. Traditional instrumented gait analysis relies on the use of a preselected link-segment model and associated biomechanical assumptions to establish the three-

dimensional position of the body segments in space. The development of traditional models for ambulation and the underlying assumptions are historically based on nondisabled individuals and may not accurately reflect the physiology and function of individuals with lower-limb prostheses [159]. Specifically, definition of the body-segment parameters and position of the joint-center locations may differ between nondisabled individuals and individuals with LLL. Of those publications included in this review, Johansson et al. addressed differences in mass and mass distribution between the prosthetic and nondisabled limbs [78]. Similarly, Segal et al. [98] and Johansson et al. [78] provided descriptions of the biomechanical models used to conduct their respective analyses. However, neither described the process for identifying or defining the joint centers. Because the estimation of kinetics is sensitive to the location of the joint centers, this may have influenced the resultant outcomes. Details regarding these decisions may help readers better understand the assumptions made by the investigators and place the results in the proper context.

As with many of the aforementioned metabolic energy expenditure studies, the large majority of gait mechanics experiments have been performed under strictly controlled laboratory conditions. Given the sophisticated equipment needed for performing full-body motion analysis, it is not surprising that these laboratories have been, and continue to be, used to collect such outcomes. Laboratory settings allow investigators to control confounding variables and improve the quality of the scientific experiments. However, most laboratories consist of flat, level terrain that may not represent a user's free-living environment. The results gathered from testing in such environments may not generalize well to real world situations. The few differences between MPKs and NMPKs related to gait mechanics may be due to the environment in which they are measured. Alternative means for acquiring temporal, spatial, kinematic, and kinetic data may offer the means to assess this possibility. Portable systems that consist of sensors for tracking body movement in the free-living environment are now available and may be used to collect gait mechanics outcomes [160–161]. The use of such systems in conjunction with traditional laboratory-based equipment may allow for the assessment of function as well as activity and/or participation [162], enhancing our understanding of how prosthetic interventions are used across a variety of environmental conditions.

The alignment of prosthetic components has also received relatively little attention in the reviewed body of

literature. Traditionally, definitive prosthetic alignment is derived from component manufacturers' recommendations and an iterative process of subjective patient feedback and observational gait analysis. Although Blumentritt et al. reported that a range of acceptable transfemoral alignments exists [163], the influence of alignment on clinical and/or scientific outcomes has rarely been studied [82,164] and is not well understood. Kaufman et al. suggested that variations in MPK gait mechanics may vary across the body of literature because of differences in prosthetic alignment [97]. While plausible, insufficient detail regarding a subject's alignment is typically provided in individual studies to support or refute this hypothesis. In the future, improved standards for documenting and reporting prosthetic-limb alignment may allow readers to better assess the influence of alignment on the study outcomes. While several publications have described the use of tools that have been developed to aid in the quantification of lower-limb prosthetic alignment [82,102,157,165–166], their regular integration into comparative research protocols or publications has yet to occur.

Environmental Obstacle Negotiation

Negotiating environmental obstacles and nonlevel terrain (i.e., curbs, ramps, steps) is commonly recognized as a requisite component of functional independence and community participation [167–168]. The potential to traverse such barriers is noted as an important mobility differentiator that transitions individuals with LLL from MFCL-1 ("limited and unlimited household ambulator") to MFCL-2 ("limited community ambulator") [169], a designation that provides them with access to additional prosthetic options under many medical insurance programs. Users also perceive a need to traverse such conditions. Legro et al. reported that lower-limb prosthesis users rated the ability to negotiate sidewalks, streets, and stairs as "highly important" (>90 on a 100-point scale) [50]. The ability to walk on slippery surfaces and hills was noted to be of lesser, yet modest (≥ 60 on a 100-point scale), importance. However, engaging in such activities while using a prosthesis is often challenging. Research has shown that negotiating nonlevel terrain requires greater muscle activity [170–171], produces altered gait patterns [23,44,172], and induces greater loads on the nondisabled limb [172] in individuals with TFLL. Given these challenges, the extent to which prosthetic interventions such as MPKs may address these restrictions is of particular scientific and clinical interest.

The evidence derived from this review revealed that the negotiation of uneven terrain by individuals with TFLL is significantly improved with the use of swing and stance MPKs than NMPKs (EES 5-A). Despite slight differences in the obstacle courses used across the reviewed studies, each offered a variety of challenging terrains (i.e., grass, rocks, sand, wood chips) commonly encountered by community-ambulating individuals. Three publications reported a significant decrease in the time needed to complete the obstacle course when using the swing and stance MPK than when using the NMPK [72,83,90], while a fourth reported a nonsignificant decrease in time associated with the task [73]. This course used by Hafner and Smith [72] and Hafner et al. [73] included additional environmental barriers (i.e., a ramp and descending stairs) that were not included in the other studies [83,90], which may have influenced the results. Interestingly, subjects initially rated as MFCL-2 in one study [72] showed nearly twice the improvement in obstacle course time than those rated MFCL-3. This may again suggest that knee MPC has the potential to address functional deficits differently across MFCL groups and should be explored further.

The ability to negotiate uneven terrain with swing-only MPKs was reported in a single cross-sectional study [88] and therefore did not contribute to an independent EES. However, subjective reports of users in this study found that many (14 of 21) perceived an improved ability to ambulate over uneven roads. This result is somewhat surprising, given that the ability to safely and efficiently negotiate uneven terrain would seem to depend more on stance-phase stability than swing-phase agility. While a swing-only MPK is purported to provide improved swing-phase response over a wider range of cadences, it is not believed to provide additional stance-phase stability that would aid in improving negotiation of environmental barriers. It is possible that the swing-phase MPC ensured that the foot was better positioned for initial contact and as a result was perceived to be more secure. At this time, the ability of swing-only MPKs to influence ambulation on uneven terrain should be considered preliminary until further corroborative work can be provided. This does, however, illustrate a need for additional research to determine more accurately whether negotiating uneven terrain is a feature of swing-phase agility, stance-phase stability, or a combination of the two.

Legro et al. reported that the ability to descend stairs is perceived by prosthesis users to be of high importance

[50]. However, in MacKenzie et al., as few as 43.5 percent of those individuals with TFL describe being able to independently perform this activity [173]. Evidence obtained through this review suggests that the use of swing and stance MPKs results in significantly improved stair descent compared with the use of NMPKs (EES 5-B). The contributing studies [72–73,90] used standardized [100] and ad hoc [100,174–175] observational outcome measures to describe the gait patterns of the study subjects as they descended stairs. Note that the psychometric properties of these measures have not yet been well established in this population. For example, Kahle et al. [90] selected the MRPP, a measure designed for children with developmental disabilities [100], while Hafner and Smith [72] and Hafner et al. [73] used the SAI [174], a novel instrument developed for individuals with LLL. However, because no other means to assess stair function have been validated with individuals with LLL, an area of future work may be to validate these or other measures of stair negotiation for use in this population. Interestingly, Jepson et al. reported that three of five subjects perceived greater challenges walking down stairs with a swing and stance MPK than with their prior NMPK [77]. Notably, several subjects in this study did not fully attend the physiotherapy program offered with the MPK. Though not explicitly stated, the program may have addressed skills needed for successful stair descent and may thus have been a reason that the users felt challenged descending stairs.

Hill descent, in contrast to stair descent, has received relatively little attention in this body of literature. Hafner and Smith [72] and Hafner et al. [73] examined the influence of MPK use on this activity. Results from these publications suggest that use of a swing and stance MPK significantly improves the speed [72–73] and pattern [72] of hill descent, but confirmatory work is needed to substantiate the EES. Buell et al. used a novel measure of stepping pattern, the HAI [175], to quantify descent pattern. As noted previously for measures of stair function, a need exists to validate and/or develop improved measures of hill function for this population.

The reported improvements in hill and stair descent with the use of a swing and stance MPK are likely due to the stance-phase features present in this type of knee joint. The stance-resistance behavior in stance-control MPKs [62] may mimic the eccentric contractions of the extensor muscles in a nondisabled knee and play a dominant role in progressing from one step to the next during stair descent

[176]. Conversely, this feature does not appear to influence a user's ability to ascend hills or stairs [73]. Because individuals with nondisabled physiology accomplish ascent patterns primarily through concentric power generating contractions of the knee extensor muscles, this finding is not unexpected. Active or powered extension of the knee joint is not provided by the MPKs that have been evaluated in the reviewed peer-reviewed literature to date, but this feature is present in at least one commercially available prosthetic knee (POWER KNEE, Össur Americas) at the time of this publication. Given the potential for prosthetic knees of this kind to promote stair ascent, investigators may consider including stair ascent as an outcome of interest in future studies.

Because knee-stability features are likely responsible for a user's ability to descend stairs and hills, it is not surprising to find a scarcity of literature describing the influence of swing-only MPKs on hill and/or stair descent. In a survey of swing-only MPK users, Datta and Howitt reported that 5 of 22 subjects perceived an improved ability to descend stairs [88]. Interestingly, a larger portion of the respondents (13 of 22) reported an improved ability to negotiate slopes and hills when using the swing-only MPK [88]. Such findings are of interest because the descent of hills and stairs would not seem to be affected by swing-phase MPC. As noted previously, it may be possible that the MP aids in better positioning the prosthetic foot for initial contact on nonlevel terrain. However, additional research would be needed to explore this possibility or explain why users perceive a benefit when using swing-only MPKs.

Given the clinical perception that MPKs are prescribed for relatively active individuals and that they promote community ambulation, it may be surprising that the ability to negotiate environmental obstacles and nonlevel terrain has not received more attention. The relative paucity of research in this area may stem from a lack of suitable resources for measuring functional ability related to the aforementioned activities. Although traditional biomechanists may have access to motion analysis laboratories, few may have the space to establish obstacle courses or include stairs and inclines within the available capture volume. Perhaps with the advancement of portable instrumentation systems [160–161], evaluation of environmental barriers in a user's natural environment may be possible. As an alternative, investigators may consider incorporating less sophisticated measures of environmental obstacle negotiation, such as timed stair

tests [177] or standardized obstacle courses [178–179], into study protocols as a way to measure these activities.

Safety

Individuals with LLL commonly present with compromised balance [4,24], which is further exacerbated by a limited ability to cope with balance perturbations using the prosthetic limb [180]. These issues likely contribute to the reported increased incidence of falls and stumbles [27,181], decreased balance confidence [26,39], and fear of falling [27] in this population. Notably, >60 percent of individuals with TFL have reported at least one fall in the past month [181] or year [27] in retrospective surveys. Not unexpectedly, Legro et al. reported that feeling balanced when using a prosthesis has been rated as highly important among these individuals [50]. Thus, any intervention that addresses some or all of these issues may be considered to be clinically relevant.

Although ambulatory safety is considered an important clinical issue, the effect of MP technology on safety outcomes has rarely been studied in the body of literature. The paucity of research in this area may be because of historical prescription paradigms that associate advanced prosthetic technology, like MPKs, with functional performance needs (i.e., ambulation variable cadence) rather than enhanced safety features. For example, patients who are currently considered candidates for MPK technology (i.e., MFCL-3 or MFCL-4) are generally not thought to be at the greatest risk for falls than typically less active and stable MFCL-2 patients. However, those MFCL-2 patients who may be at the greatest risk for falls are not currently deemed candidates for MPKs.

Results of this systematic review indicate that, when compared with NMPKs, swing and stance MPKs significantly decrease the number of subject-reported stumbles and falls (EES 6-A), while reducing frustration with falls (EES 6-B) and increasing balance confidence (EES 6-C). Remarkably, Kahle et al. noted the frequency of falls decreased by as much as 64 percent with use of the MPKs [90]. For individuals rated as MFCL-2, Hafner and Smith noted an even more impressive 80 percent decrease [72]. Mechanistic studies of individuals' biomechanical responses to physical perturbations while wearing both swing and stance MPKs and NMPKs similarly show improvements in standing [97] and walking [102] balance while using MPKs. From a clinical perspective, this evidence may have important long-term health implications. The potential for an intervention to mitigate falls,

the subsequent injuries, and the associated medical costs (or productivity losses) seems intriguing and may lend itself to future scientific explorations.

A noted limitation of those studies that examined subject-reported falls and stumbles [72–73,77,90] was the use of retrospective, rather than prospective, user reports. Retrospective reports are generally believed to be as specific but less sensitive than prospective data collection methods that use a calendar or diary [182]. Recent reviews have recommended that falls should be recorded using prospective recording systems [183] with a weekly or monthly recall period [182] in order to avoid forgetting events or including events outside of the desired time frame. Prospective studies related to the frequency of adverse events such as stumbles and falls may therefore be a priority for future research. Similarly, exploring the means to objectively measure adverse events may be beneficial [184–186].

Based on these findings, patient candidacy is an area of research that logically warrants further exploration. As previously noted, the prescription of MPKs has been historically reserved for patients who are capable of achieving variable cadence (i.e., MFCL-3). This is likely because of manufacturers', clinicians', and reimbursement agencies' original focus on those characteristics of the MPK that addressed the needs of the active user (i.e., walking faster, minimizing metabolic energy expenditure). However, an increasing body of evidence related to stability features (and associated safety outcomes) in recent years demonstrates the potential for MP technology to benefit less active and less stable patients. In light of the existing evidence, it seems prudent to consider that prescribing MPKs should not be limited to those patients for whom variable cadence is possible but extended to those patients who demonstrate challenges with stability [187].

Preference and Satisfaction

Physiological or biomechanical responses to interventions do not necessarily translate into those outcomes most desired or deemed important by individuals with LLL. The role of patient preference and/or satisfaction has long guided decisions in the provision of prosthetic care, but only recently has it begun to receive attention in the prosthetic literature [188]. Although population-based surveys of overall use and satisfaction with prostheses (and/or prosthetic services) among individuals with LLL exist [181,189–192], none of these describe

how preference or satisfaction is influenced by specific prosthetic components.

This systematic review revealed that, as a group, users preferred both swing and stance MPKs (EES 7-A) and swing-only MPKs (EES 7-B) to NMPKs. While subject groups included in the reviewed studies often indicated an overall preference for the swing and stance MPK, this was not a universal outcome because there were individuals who preferred the NMPK prosthesis. Interestingly, preference was not always correlated with performance. In several instances, outcomes were noted to improve with use of the MPK, yet those subjects still preferred the NMPK [90]. This again raises interesting and important questions regarding component candidacy and prescription criteria for MPKs. While user choice has been identified as an important factor when matching prosthetic technology to the patient [193], further investigation into component preferences among individuals with TFL is warranted to better understand the social, physical, and psychological characteristics associated with prosthetic knee preferences. Notably, patient characteristics such as time since amputation, previous prosthesis experience, and activity level may all be factors that influence prosthetic knee preference. Likewise, additional research is needed to determine which characteristics of the prosthetic knee (i.e., performance, weight, cosmesis) drive or motivate user preference. This latter topic was briefly addressed by Orendurff et al., who noted that several subjects in their study offered unsolicited preference for the swing and stance MPK over a stance hydraulic prosthetic knee because of perceptions that the MPK resisted stumbles and accommodated to any walking speed they chose [81]. Interestingly, these comments appear to corroborate two EESs (4-A and 6-A) generated within this systematic review.

In addition to increased preference, the use of swing and stance MPKs also appears to be associated with improved patient satisfaction when compared with the use of NMPKs among individuals with unilateral TFL (EES 7-C). The contributing studies all measured satisfaction with the first question on the PEQ, which states, Over the past 4 wk, rate how happy you have been with your current prosthesis? Although this question is directed at user satisfaction, it is not validated as a stand-alone item of the PEQ [50] and therefore may not reflect the desired construct. Additional psychometric development would be required to confirm that this question is a stand-alone measure of satisfaction. Interestingly, many studies that

describe the satisfaction of prosthesis users elect to use ad hoc outcome measures. One reason may be the relative lack of validated instruments to assess satisfaction in this population. The Orthotic and Prosthetic Users' Survey is one population-specific measure that has undergone both reliability and validity testing as part of its psychometric development [194]. Other measures, such as the Satisfaction with a Prosthesis [195], Trinity Amputation and Prosthesis Experience Scales [196], Orthotic and Prosthetic Outcomes Tool [197], and Attitude to Artificial Limbs Questionnaire [198], have received preliminary testing in the literature and may yet require additional validation before they can be universally recommended. However, future studies may consider continued psychometric development of these measures and/or inclusion of such measures in intervention studies if satisfaction is deemed to be a construct of importance.

One concern related to preference includes the user's expectations or the associated potential for bias. Notably, MPKs have received considerable attention in the general [199] and consumer [200] literature. It is therefore likely that some or all of the subjects in the reviewed studies may have received some exposure to the intervention(s) prior to their participation. Given that blinding was not used in any of the studies relevant to this outcome topic, the reported preference for the MPKs may have been related to the novelty of the intervention. As noted previously, we acknowledge the challenges with blinding such interventions. However, without further assessment of the factors that influence prosthetic knee preference, a strong and unbiased link between MPKs and user satisfaction cannot be established. The relationships between patient preference, opinions on new or emerging technology, and clinical outcomes also remain largely unexplored within lower-limb prosthetics but are likely to be a critical factor in understanding and establishing positive PROs [193]. Given these considerations, it may be important for future outcome measures to address issues of satisfaction by incorporating the concept of patient expectation.

Economics

Growing healthcare costs have prompted changes in the way interventions are examined and provided. As a result, researchers, clinicians, and policy makers are increasingly aware of a growing need for economic analyses that evaluate intervention outcomes in context with the costs required to provide them. The reviewed body of literature included several types of economic analyses, including cost utility

analyses and cost consequence analyses [201]. In these analyses, cost may include acquisition costs, healthcare costs, and/or other societal costs (e.g., housing modifications, personal care assistance, productivity losses). Similarly, utility pertains to the consequences of the intervention, including both the QOL and quantity of life gained through its provision. It is typically expressed as a QALY. Although the means for acquiring this information and scope of included information vary among the reviewed studies, the goal of each was to examine and weigh the differences in costs, utility, and cost-utility ratios for the compared interventions. We examined costs associated with the prosthetic knees from several perspectives in this review. First, we found the initial MPK acquisition costs to be significantly greater than the NMPK (EES 9-A). While readers may likely accept this information without the derived EES, recall that the purpose of this review was to generate empirical evidence based on the significant findings reported in the peer-reviewed literature. Here, the economic studies [89,92,105] elected to measure and compare the initial cost of the interventions, thus providing the information needed to derive the EES. While not unexpected, EES 9-A becomes more interesting when contrasted against the broader societal costs (EES 9-B).

It has been recommended that economic analyses be performed from a societal perspective to best represent the public interest over that of any specific group (e.g., reimbursement agencies or patient groups) [202]. Two of the reviewed studies approached costs in this manner and included analysis of expenses beyond the prosthetic prescription, including medical visits, pharmaceutical prescriptions, hospitalizations, transportation, home modifications, housekeeping assistance, and productivity losses [89,92]. For example, Gerzeli et al. reported mean intervention costs of €18,616 (\$22,348) and €3,600 (\$4,328) for the MPK and NMPK prostheses, respectively [89]. However, after considering all societal costs related to intervention maintenance, medical services, transportation, caregiving, and productivity losses for the 50 subjects enrolled in each group in the study, mean costs were €66,669 (\$80,162) and €66,927 (\$80,473), respectively. The largest societal cost differences in the reviewed literature were attributed to the category of productivity losses. Both Gerzeli et al. [89] and Seelen et al. [92] noted larger productivity losses with NMPK users than MPK users, suggesting that the MPK may be more effective at allowing users to return to work. Thus, the available evidence indicated that total costs for prosthetic rehabilitation from a societal perspective were

equivalent between swing and stance MPKs and NMPKs (EES 9-B).

The reviewed economic analyses ultimately reported the required cost to gain an additional QALY through the prescription and use of a swing and stance MPK compared with an NMPK. The incremental cost per QALY varied from €3,218 (\$4,132) [105] to €35,971 (\$43,251) [89] when considering only prosthesis cost. The difference in these incremental costs per QALY may be attributed to the greater cost of the NMPK prosthesis and/or the greater QALY associated with the MPK prosthesis described by Brodtkorb et al. [105]. However, when including societal costs, there is a reported cost savings of €614 (\$738) per QALY with the prescription and use of a swing and stance MPK [89]. In an effort to interpret these numbers, benchmarks have been proposed to establish a reasonable cost per QALY. Established values appear to range between \$30,000 and \$100,000 [203]. Based on this evidence, it would appear that the prescription and use of swing and stance MPKs might be considered a cost-effective technology and, despite initially being more expensive, would appear to be an effective alternative for reestablishing a life that is both of higher QOL and longer duration.

Note that the data provided through economic analyses may be interpreted differently by different decision makers. The reviewed studies [89,92,105] were all conducted within countries with nationalized healthcare systems. In such cases, the societal costs may be of specific interest to national agencies from a financial perspective. Conversely, many individuals with LLL in the United States subscribe to private medical insurance programs. These private reimbursement companies may not weigh societal costs in the same manner as a national agency. In such cases, the initial acquisition costs may be prioritized and may therefore be favored in conducting future cost utility analyses. One means of addressing this potential challenge is to report both acquisition and societal costs, as done by Gerzeli et al. [89]. Incremental costs may then be calculated from either perspective.

Health and Quality of Life

QOL has become an increasingly popular concept in the assessment of outcomes. Though challenging to define, QOL often relates to the subjective elements that contribute to an individual's happiness and satisfaction with life. This broad concept has historically included such elements as health, education, family life, vocational

experiences, and financial status. The term HRQL, often used interchangeably with general health status [204], reflects those QOL elements that influence (or are influenced by) health. HRQL has been noted to describe the physical, mental, social, and emotional aspects of health and may include personal relationships, functional ability, pain, perceptions of self and others, satisfaction with life, and well-being [138,205]. As may be expected, self-reported HRQL varies greatly among individuals with LLL [138,206–207]. Contributing factors are not well understood, although a study by Asano et al. suggested that depression, prosthetic mobility, and social support are those factors most likely to predict HRQL in this population [206]. Comparisons of HRQL between individuals with LLL and nondisabled individuals are rare [48–49], but those that exist have reported several key significant differences. Hagberg and Brånemark [49] reported a significantly decreased overall HRQL, as measured by all eight dimensions of the SF-36 [52], among 97 individuals with nondysvascular unilateral TFL when compared with those of age- and sex-matched persons. Similarly, Dougherty found that 46 Vietnam war veterans with TFL reported significantly lower SF-36 physical function and general health subscale scores than that of age- and sex-matched controls [48]. Given the reported reduced QOL in this population, HRQL measures are often included in studies of interventions that are believed to influence general health. The QALY, a calculated preference for a health state (i.e., weighted on a scale from 0 [dead] to 1 [optimal health]), multiplied by the time (years) spent in that health state, is the recommended outcome for economic analyses [202] because intermediate outcomes such as metabolic energy expenditure, gait speed, and cognitive demand may not well reflect the broad concepts of health and well-being. The evidence identified in this systematic review indicated that the use of swing and stance MPKs results in a significantly greater number of QALYs than the use of NMPKs (EES 8-C). In both cases, the preference for the health state was determined by using the study subject's (i.e., prosthesis user's) EuroQol EQ-5D scores [106]. Note that one of these studies used a within-subjects design that required MPK users to reflect back on their prior experience with the NMPK, perhaps biasing the results of the subjective data to the current intervention (i.e., the MPK) [105]. Notably, the QALY difference reported in this study (2.98) was substantially larger than that (0.42) obtained by Gerzeli et al. [89], who used a larger group design. Thus,

additional prospective research may be needed to confirm the incremental QALY provided by an MPK compared with an NMPK.

Interestingly, the evidence derived from this systematic review indicates that using a swing and stance MPK, compared with an NMPK, results in an equivalent level of general health (ESS 8-A) and significantly increased level of well-being (EES 8-B). While both EESs address one of the aforementioned subdomains of HRQL, the discrepancy between them may be the result of the items contained within the selected outcome measures. General health, as described by EES 8-A, was measured by all contributing studies using the SF-36 [52]. SF-36 general health subscale questions poll the respondent about his or her overall health, specifically addressing such aspects as “getting sick.” Thus, these questions may not draw attention to health related to LLL or prosthesis use. Many individuals with LLL also experience comorbidities that may limit their perception of physical functioning with respect to their general health. Alternatively, well-being (EES 8-B) was measured exclusively using the PEQ well-being subscale [208]. The PEQ is a population-specific measure designed to solicit information regarding use of the prosthesis. PEQ well-being subscale questions relate to a respondent's satisfaction with how well things have “worked out since [the] amputation” and will likely draw the respondent's attention to his or her condition and the prosthesis. Hence, if an MPK does indeed improve QOL, it should not be surprising that the PEQ is more sensitive than the SF-36 to the changes produced by this intervention.

Clearly, measuring HRQL is a challenge. Selecting and using a generic outcome measure allows for comparisons to normative values in nondisabled (or other related) populations. However, generic HRQL measures may not be as sensitive to issues of concern in the population of interest. Population- or condition-specific measures are likely to be more specific and sensitive but may not allow for comparisons between individuals with different conditions because normative data may not exist [209]. One potential solution is the inclusion of both types of measures in a study, an alternative not often selected in the reviewed studies. Measuring health in the population of individuals with LLL also presents several unique challenges. In addition to issues of physical function, this population also experiences pain [136], depression [206], lowered energy [136–137], and sleeplessness [137], all of which can affect overall health. Many of these are condition-related, and thus, may respond to changes in prosthetic

interventions and may be considered in future outcome studies.

Lastly, individual expectations with rehabilitation may also have the potential to influence HRQL. Although the connection between expectations and HRQL remains largely unexplored [210], clinical experience suggests that outcomes are often affected by the patient's perceptions of rehabilitation. Methodological approaches to developing expectations, setting goals, and individualizing treatment, such as the Patient Generated Index [211] and Goal Attainment Scaling [212], have been used to assess the preferences of individual prosthesis users but not in conjunction with an interventional trial. They may be of benefit in exploring the changes in QOL associated with specific prosthetic interventions such as those reviewed here.

Limitations of Review

This work is not without limitations. We intended the question developed to guide this systematic review to address the most common clinical population, individuals with unilateral TFL, in which MPKs are prescribed and used. By definition, this excluded individuals with bilateral TFL and those with more proximal levels of LLL for which the use of MPKs may be appropriate. While we excluded studies pertaining to the use of MPKs among these populations from the formal review process and the creation of the EESs, we considered and included them within the discussion as appropriate.

The prosthetic knee technologies discussed in this review (i.e., swing and stance MPKs, swing-only MPKs, and NMPKs) represent categories of components. Subtle differences in behavior among specific models (e.g., Compact C-Leg and RHEO KNEE) and outcomes achieved with their use are not well understood. Thus, while we have generalized the EESs developed in this review to the specific type of prosthetic knee (i.e., swing and stance or swing-only), readers are cautioned to note that the published literature reflects a small subset of those prosthetic knees that are commercially available and it is derived predominantly from outcomes related to two specific models (i.e., Compact C-Leg and SmartIP). Because most commercially available MPKs have yet to be the focus of scientific study, outcomes related to their use may be loosely extrapolated based on functional similarities to those prosthetic knees that have been studied. A detailed comparison of the functional similarities and differences among different models is beyond the scope of this review, so readers

must use their own clinical judgment when extrapolating the evidence presented here in relation to other MPKs.

This systematic review may be limited because it includes publications up to October 2009. In the interim period between the literature search and final submission of this review for publication, additional studies pertinent to the topic of this review were published [213–216]. Readers are encouraged to consider these publications in light of the findings presented here.

Another perceived limitation of this review may be the potential for bias by one of the review authors (B. H.), who also coauthored two publications included in this review. To address this potential bias, an alternate reviewer scored these publications rather than the study author. Similarly, we believe that the use of a systematic review process and standardized quality assessment mitigated this potential bias.

The described review process [71] and its associated classification and rating systems may likewise be perceived to be a limitation of the review because they have received little attention in the literature. The AAOP developed the guidelines for review used here to evaluate O&P literature and subsequently to create evidence reports on relevant O&P healthcare topics. Although this system is relatively new, note that no universally accepted system exists to rate methodological quality [217]. Furthermore, these guidelines have successfully been used in other systematic reviews of O&P interventions [74,109–110]. We acknowledge that additional work may be required to evaluate the reliability of this review process, to assess the effect of weighting IV and EV criterion, and to compare the outcomes generated here to other standardized reviews, such as those established by the Cochrane Collaboration [218].

Lastly, an ideal EBP approach to clinical decision-making recognizes that multiple sources of information exist and each should be appropriately considered when formulating and rendering a decision. Sources of knowledge that have been identified as valuable components to EBP include empirical evidence, experiential evidence, pathophysiologic rationale, patient values and preferences, and system features (i.e., facilitators of care) [219]. The relative importance of each of these areas must be considered and then weighed in the context of the individual patient in order to arrive at the best clinical decision [219–220]. The extent to which each of these sources of evidence is used in making a clinical decision is beyond the scope of this review but clearly depends on

which sources are available. The findings of this systematic review represent a comprehensive source of empirical evidence, one that has been derived from a wide variety of peer-reviewed, published research studies. It should be acknowledged that the most effective use of these findings will not occur in isolation but rather when appropriately integrated with the other sources of information and knowledge that contribute to effective EBP.

CONCLUSIONS

We reviewed the body of scientific, peer-reviewed literature in an effort to identify changes in outcomes associated with the prescription, fit, and use of MPKs when compared with NMPKs among individuals with unilateral TFL. We identified nine outcome topics (metabolic energy expenditure, activity, cognitive demand, gait mechanics, environmental obstacle negotiation, safety, preference and satisfaction, economics, and health and QOL) and generated EESs related to each topic. Varying levels of evidence exist to indicate that the prescription, fit, and use of swing and stance MPK lead to changes in outcomes for individuals with unilateral TFL when compared with NMPKs.

Moderate evidence exists to suggest that swing and stance MPKs are associated with increased confidence during ambulation, increased self-reported mobility, reduced self-reported cognitive demand while walking, improved self-reported well-being, and equivalent overall societal costs when compared with NMPKs. Low evidence indicates that these MPKs are also associated with increased walking speed on uneven terrain, improved gait patterns in stair descent, decreased numbers of falls, greater user satisfaction, greater user preference, decreased rate of O₂ consumption while walking at SSWS, increased SSWS, and increased knee moment in early stance. Moderate to low evidence suggests that swing and stance MPKs and NMPKs result in similar levels of activity, cognitive burden while walking, self-reported general health, rate of O₂ consumption at SSWS, O₂ cost over a range of walking speeds, and spatial symmetry. Insufficient evidence exists to assess the effect of swing and stance MPKs on temporal symmetry, peak knee-flexion angle, and prosthetic-side hip power. Low evidence suggests that swing-only MPKs are associated with increased user-reported preference compared with NMPKs. Moderate to low evidence indicates that swing-only MPKs produce similar rates of O₂ consumption

while walking, cognitive burden while walking, SSWS, and spatial symmetry to NMPKs. No evidence suggests that NMPKs provide improved clinical outcomes when compared with MPKs within this body of literature.

This article represents the most comprehensive and detailed collection of evidence regarding the influence of MPKs on the rehabilitation of individuals with unilateral TFL. Given the current level of empirical evidence, we can conclude that MPKs are indicated for those individuals who require an increase in safety or an improved ability to descend stairs and/or negotiate uneven terrain. The provision of an MPK is also likely to be met with improved patient preference and satisfaction, an improved perception of mobility, and a reduced perception of the effort required for ambulation. Further, MPKs appear to offer these benefits at equivalent total prosthetic rehabilitation costs compared with traditional alternatives. Based on the available evidence, MPKs do not appear to influence outcomes related to O₂ consumption, physiological measures of cognitive demand, or the amount of daily activity performed. These findings may be used to indicate those individuals with unilateral TFL for whom this prosthetic knee technology is most appropriate.

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