A systematic literature review of the effect of different prosthetic components on human functioning with a lower-limb prosthesis

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Abstract—A correct prosthetic prescription can be derived from adapting the functional benefits of a prosthesis to the functional needs of the prosthetic user. For adequate matching, the functional abilities of the amputees are of value, as well as the technical and functional aspects of the various prosthetic components. No clear clinical consensus seems to be given on the precise prescription criteria. To obtain information about different prosthetic components and daily functioning of amputees with a prosthesis, we performed a systematic literature search. The quality of the studies was assessed with the use of predetermined methodological criteria. Out of 356 potentially relevant studies, 40 studies eventually qualified for final methodological analysis and review. Four satisfied all the criteria and were classified as A-level studies, 26 as B-level, and 10 studies as C-level studies. Despite a huge amount of literature, our formal clinical knowledge had considerable gaps concerning the effects of different prosthetic components and their mechanical characteristics on human functioning with a lower-limb prosthesis. Therefore, with regard to prosthetic guideline development, we must still largely rely on clinical consensus among experts. The integration of knowledge from research with the expert opinion of clinical professionals and the opinions and wishes of consumers can form a solid base for a procedure on guideline development for prosthetic prescription.

Key words: artificial limbs, biomechanical parameters, human functioning, lower-limb amputation, physiological parameters, prosthesis, prosthetic foot, prosthetic knee, prosthetic prescription, prosthetic suspension, socket, stump, systematic review.

INTRODUCTION

Prosthetic prescription for patients with lower-limb amputation is primarily based on empirical knowledge. Many options are available for different prosthetic components; however, prescription criteria are based mainly on subjective experiences of physicians, therapists, and prosthetists [1,2]. On the other hand, third-party payers frequently require justification for purchasing costly prostheses [2]. Also, clarity for the customer is required since quality of care is becoming more important. In the ideal situation, prosthetic prescription is based on adjusting the mechanical characteristics of a prosthesis to the functional needs of the prosthetic user [3], yet no clinical guidelines seem to be available for this use.

The development of scientifically based clinical guidelines is a way of making health care more consistent and efficient and diminishes the gap between what clinicians do and what scientific evidence supports. A systematic

Abbreviations: CVZ = Dutch Health Care Insurance Board, EMG = electromyographic, RCT = randomized controlled trial, ROM = range of motion, SACH = Solid Ankle Cushion Heel. This material was based on work supported by the Dutch Health Care Insurance Board (CVZ).
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literature review is the first step in clinical guideline development. It may also highlight knowledge gaps in the existing evidence [4]. To our knowledge, no scientifically based guidelines for lower-limb prosthetic prescription exist. Also, no consensus seems to exist among different professionals with regard to the criteria for selecting prosthetic components related to the functional abilities and needs of patients. In this perspective, the Dutch Health Care Insurance Board (CVZ) has initiated a national project to develop clinical guidelines for lower-limb prosthetic prescription to obtain consensus among clinicians, manufacturers, and insurance companies in the Netherlands. The first step is to extract as much scientifically based knowledge from the literature as possible. In this respect, two types of studies can be distinguished: (1) clinical studies focusing on motor performance or daily functioning with a lower-limb prosthesis and (2) technical studies focusing on the mechanical characteristics of prosthetic components without specifically human functioning. In view of prosthetic guideline development, only studies addressing motor performance and human functioning with a lower-limb prosthesis are considered relevant. Hence, this review will be restricted to these clinically oriented studies.

**METHOD**

**Procedure**

We performed a systematic search using the Medline database (from 1966), Current Contents (from 1996), The Cochrane Database (2001 issue), and Psyclit (from 1971) until February 2001. A combination of the following key words and their synonyms was used: lower-limb prosthesis, lower-limb amputation, prosthetic prescription, prosthetic foot, prosthetic knee, prosthetic suspension, stump, socket, and physiological and biomechanical parameters. Also we checked the references from the retrieved articles and (systematic) reviews to extend the search.

Based on their abstracts, studies were further considered when:

1. The papers were written in the English, German, or Dutch languages.
2. The study design was either a randomized controlled trial (RCT), a cohort study, or a case-controlled study, allowing at least some control of confounding factors.
3. The study investigated patients with a trans femoral, through-knee, or transtibial amputation.
4. The study used subjective findings, activities of daily living measures, and/or functional characteristics of human stance or gait (spatio-temporal, physiological, kinematic, kinetic, or electromyographic [EMG] parameters) as outcome variables.
5. The study evaluated specific components of the prosthesis.
6. The goal of the study was to provide insight into the effects of different prosthetic components on human functioning with a lower-limb prosthesis.

**Methodological Criteria**

After this abstract-based selection of relevant studies, we assessed the methodological quality of each article using a checklist of 13 predetermined criteria. This checklist was based on the integration of two existing criteria lists for quality assessment [5,6], which were originally developed to evaluate randomized controlled trials (see Appendix, which can be found in the online version only [7,8]). Some criteria were adapted for nonrandomized controlled trials. Each criterion was scored at two levels: invalid/no “0” and valid/yes “1.” If a criterion was not applicable, it was scored “0.” Two reviewers (HL and CH) independently analyzed the studies. If the reviewers found a discrepancy, they achieved consensus in the second instance.

For this review, the included studies were required to sufficiently control for selection and measurement bias. Studies were classified as—

- **A-level studies**: Studies with a total score of at least 11 points or more, including 6 points out of the A- and B-criteria, including a positive score for blinded outcome assessment (criterion B7) and timing of the measurement (criterion B8).

- **B-level studies**: Studies with a total score between 6 and 10 points, including a positive score for timing of the measurement (criterion B8).

- **C-level studies**: Studies with a total score of at least 6 points out of the A- and B-criteria with an invalid score on criteria B7 and B8.

Therefore, only the studies in which the total score of the A- and B-criteria was at least 6 out of a possible 9 points were used in the best-evidence synthesis.
RESULTS

Selection of Studies

Out of 356 potentially relevant studies on lower-limb prosthetic functioning, we selected 64 studies based on their abstracts (see the Figure for the selection algorithm according to the QUOROM statement [9]). References from the retrieved studies and (systematic) reviews yielded 72 more papers. We similarly assessed the abstracts of these 72 studies, selecting 17 additional studies and fulfilling the preliminary selection criteria. Most of the studies that did not meet these criteria were either uncontrolled case series or case reports (criterion A1) or their primary purpose was not related to human functioning with a prosthesis (criterion B6). For instance, many articles focused only on amputation techniques or on the technical possibilities of early prosthetic fitting. Hence, we methodologically assessed the full texts of 81 selected studies using the checklist of 13 criteria just mentioned [1–3,10–87]. Based on these assessments, 40 studies received an A-, B- or C-level classification and were included for final review (Tables 1 and 2). An important reason for excluding the 41 other studies was that the selection of the study sample was so poorly described that the results could not be reliably interpreted from a clinical perspective.

No classical RCTs were identified, yet all included studies used crossover designs that allowed sufficient control for confounding. Four papers were classified “A-level studies” [17,18,67,68], twenty-six “B-level studies” [2,3,13,16,20,22,23,27,30,36,37,42,44–46,52,53,55–58,61,66,69,71,77,81,83], whereas ten studies were classified “C-level studies” [1,15,35,52–54,59,63,76,77,81,83]. The main difference between the A- and B-level studies was a negative score on the “blinded assessment” (criterion B7). Indeed, only Postema et al. [67,68], Boonstra et al. [17,18], and Gailey et al. [35] (C-level study) reported that their subjects were blinded to the intervention. Seven studies applied no randomization of the sequence of interventions [2,20,42,46,52,61,71] and, therefore, had a negative score on criterion A4. Of the other studies, only Postema et al. described which randomization procedure was applied [67,68]. The randomization was done with the aid of a dice, and the code was broken only after the entire trial had been completed. Seven articles scored negatively for functional homogeneity [16–18,22,23,30,81]. Based on the provided subject characteristics, the study sample could be concluded to be considerably heterogeneous for activity level, which was not accounted for by a stratified analysis.

In some studies, the prosthetic components, other than the component investigated, were not kept constant, resulting in a “0” on criterion B6 [1,15,39,44,55,56,61,63,76]. In eight studies on prosthetic mass [35,39,52–54,59,63,76] and the Board’s study on prosthetic socket design [15], the subjects were not allowed sufficient time to adapt to the intervention, so they received a negative B8 score. Eight studies did not indicate possible dropouts [1,3,16,30,52,53,76,81]. Insufficient information was available about how many subjects were eventually subjected to the intervention. Therefore, this study received a negative score on criterion C10. In six studies, the authors failed to provide adequate measures of variability, even though such data were necessary to interpret the results [1,13,15,63,71,81].

Selected Study Results

The selected studies on functioning with a lower-limb prosthesis allowed a division in four categories based on their focus of attention: effects of different (1) prosthetic feet, (2) prosthetic knees, (3) prosthetic sockets, and (4) prosthetic mass. The prosthetic foot was the focus of investigation in 28 studies [1–3,13,16,20,22,23,30,36,44,45,52,53,55–58,63,66–69,71,76,77,81,83]. The main clinical findings are shown in Table 3. The prosthetic knee was the focus in five studies [17,18,42,46,61], the prosthetic socket in one study [15], and prosthetic mass in six studies [25,35,37,39,54,59], with the main clinical findings in Table 4.

As dependent variables, time-distance parameters are probably the most easily obtainable objective data for evaluating changes in a patient’s gait performance [88]. From a clinical point of view, such parameters are also readily interpretable. Hence, many of the included studies focused primarily on these parameters as well as on kinematic variables [1–3,13,15,16,22,30,36,37,39,45,52,53,56,57,59,61,63,66–68,71,76,77,81,83]. Fifteen studies used oxygen uptake [13,17,20,25,35,44,45,52,54,58,59,63,76,81,83], and two studies assessed heart rate [46,63]. To evaluate the difficulty of walking, 1 study used the Borg scale [56], 2 studies evaluated patient satisfaction [20,67], and 21 studies used walking speed to investigate differences between specific prosthetic components [1,2,13,16,20,22,25,39,46,52–54,61,63,66,68,69,71,76,77,81].
Potentially relevant studies identified in Cochrane (n = 13), Medline (n = 337), Psyclit (n = 1), Current Contents (n = 5)  
\[ n = 356 \]

Studies from primary search that met the primary abstract-based inclusion criteria  
\[ n = 64 \]

Studies retrieved from extended search (references)  
\[ n = 72 \]

Studies from extended search that met the primary inclusion criteria (abstract-based)  
\[ n = 17 \]

Studies selected for standardized methodological assessment  
\[ n = 81 \]

Studies included for final review, based on best-evidence synthesis  
\[ n = 40 \]

\[ n = 292 \]

\[ n = 55 \]

\[ n = 41 \]

Figure. Selection algorithm.
<table>
<thead>
<tr>
<th>Author</th>
<th>Parameters</th>
<th>Selection</th>
<th>Intervention</th>
<th>Statistical Validity</th>
<th>Total Score</th>
<th>Level of Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barth et al. [13]</td>
<td>Walking speed, step length, cadence, $V\cdot O_2$ (mL/kg/min, mL/kg/m), joint motion ($\cdot$), time-related variables</td>
<td>3 traumatic TT, 39 ± 10; 3 vascular TT, 64 ± 5</td>
<td>1 1 1 1 4</td>
<td>1 0 0 1 1 4</td>
<td>1 0 0 1</td>
<td>8 B</td>
</tr>
<tr>
<td>Boonstra et al. [16]</td>
<td>Walking speed, joint motion ($\cdot$), time-related variables</td>
<td>20–70</td>
<td>1 0 1 0 2</td>
<td>1 1 0 1 1 4</td>
<td>0 1 1 2</td>
<td>8 B</td>
</tr>
<tr>
<td>Casillas et al. [20]</td>
<td>$V\cdot O_2$ (mL/kg/min, mL/kg/m), satisfaction (0–100), walking speed</td>
<td>12 traumatic TT, 50 ± 14; 12 vascular TT, 73 ± 7</td>
<td>1 1 1 0 3</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>Cortes et al. [3]</td>
<td>Kinetic, kinematic, and time-related variables</td>
<td>8 traumatic TT, 19–49</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>0 1 1 2</td>
<td>10 B</td>
</tr>
<tr>
<td>Culham et al. [22]</td>
<td>Walking speed, stride length, cadence, time-related variables, knee motion ($\cdot$)</td>
<td>9 TT, 39–49</td>
<td>1 0 1 1 3</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>Culham et al. [23]</td>
<td>Electromyographic (EMG) activity of vastus lateralis and medial hamstrings, bilaterally</td>
<td>10 TT (9 vascular, 1 traumatic), 32–79</td>
<td>1 0 1 1 3</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>Doane &amp; Holt [30]</td>
<td>Center of mass displacement and velocity, joint motion ($\cdot$), time-related variables</td>
<td>55–67</td>
<td>1 0 1 0 2</td>
<td>1 1 0 1 1 4</td>
<td>0 1 1 2</td>
<td>8 B</td>
</tr>
<tr>
<td>Gitter et al. [36]</td>
<td>Joint muscle power output (W)</td>
<td>5 traumatic TT, 20–50</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>11 B</td>
</tr>
<tr>
<td>Goh et al. [1]</td>
<td>Walking speed, time-related variables</td>
<td>6 TT, 53 ± 9; 5 TF, 48 ± 11</td>
<td>1 1 1 0 3</td>
<td>1 0 0 1 1 3</td>
<td>0 1 0 1</td>
<td>7 C</td>
</tr>
<tr>
<td>Hsu et al. [44]</td>
<td>$V\cdot O_2$ (mL/kg/min, mL/kg/m)</td>
<td>5 TT, 27–36</td>
<td>1 1 1 1 4</td>
<td>1 0 0 1 1 3</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>Huang et al. [45]</td>
<td>$V\cdot O_2$ (mL/kg/min), joint motion ($\cdot$)</td>
<td>8 traumatic TT, 30 ± 6; 8 vascular TT, 63 ± 5</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>11 B</td>
</tr>
<tr>
<td>Lehmann et al. [52]</td>
<td>$V\cdot O_2$ (mL/kg/m), walking speed, GRFs (N/kg), joint motion ($\cdot$)</td>
<td>9 TT, 21–53</td>
<td>1 1 1 0 3</td>
<td>1 1 0 0 1 3</td>
<td>0 1 1 2</td>
<td>8 C</td>
</tr>
<tr>
<td>Lehmann et al. [53]</td>
<td>Metabolic rate (cal/kg/min, cal/kg/m), walking speed, GRFs (N/kg), joint motion ($\cdot$)</td>
<td>10 TT, 21–36</td>
<td>1 1 1 1 4</td>
<td>1 1 0 0 1 3</td>
<td>0 1 1 2</td>
<td>10 C</td>
</tr>
<tr>
<td>MacFarlane et al. [56]</td>
<td>Borg scale (0–20 scale)</td>
<td>7 traumatic TT, 19–49</td>
<td>1 1 1 1 4</td>
<td>1 0 0 1 1 3</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>MacFarlane et al. [55]</td>
<td>Linear and temporal and gait symmetry variables</td>
<td>7 traumatic TT, 19–49</td>
<td>1 1 1 1 4</td>
<td>1 0 0 1 1 3</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
<tr>
<td>MacFarlane et al. [58]</td>
<td>Linear and temporal and gait symmetry variables</td>
<td>5 traumatic TF, 37 ± 5</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>11 B</td>
</tr>
<tr>
<td>MacFarlane et al. [57]</td>
<td>$V\cdot O_2$ (mL/kg/min, mL/kg/m)</td>
<td>5 traumatic TF, 37 ± 5</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>11 B</td>
</tr>
<tr>
<td>Menard et al. [2]</td>
<td>GRFs (N/kg), walking speed</td>
<td>8 traumatic TT, 31–51</td>
<td>1 1 1 0 3</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3</td>
<td>10 B</td>
</tr>
</tbody>
</table>
Many different comparisons were made. Furthermore, differences in selected and presented outcome parameters among studies investigating the same prosthetic components did not allow a true meta-analysis of the results. Hence, we decided to focus our review on the consistency of clinical findings across studies on the same topic. In the case of inconsistency, methodological quality was used for final interpretation.

### Studies on Prosthetic Feet

One A-level study [67], fifteen B-level studies [2,3,13,16,20,22,30,56,57,66,69,71,77,81,83], and five C-level studies used time-distance parameters to compare different types of prosthetic feet [1,52,63,76]. In general, few discriminative effects were found. For instance, in most studies the self-selected (comfortable) walking speed was not influenced by the type of prosthetic foot in

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**Table 1. (Continued)**

Assessment of methodological aspects of reviewed studies on prosthetic feet.*

<table>
<thead>
<tr>
<th>Author</th>
<th>Parameters</th>
<th>Subjects (Reason &amp; Level of Amputation, &amp; Age [yr])</th>
<th>Selection</th>
<th>Intervention</th>
<th>Statistical Validity</th>
<th>Total Score</th>
<th>Level of Evidence</th>
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</thead>
<tbody>
<tr>
<td>Nielsen et al.</td>
<td>Walking speed, $\text{VO}_2$ (mL/kg/min, mL/kg/m), heart rate</td>
<td>7 traumatic TT, 27 ± 7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Perry et al.</td>
<td>Walking speed, cadence, joint motion (*), and velocities (rad/s)</td>
<td>10 vascular TT, 49–72</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Postema et al.</td>
<td>Preference (0–10 scale)</td>
<td>10 traumatic/oncologic TT, 34–66</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Postema et al.</td>
<td>Walking speed, cadence, joint motion, GRFs, energy absorption</td>
<td>10 traumatic/oncologic TT, 34–66</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>1</td>
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<tr>
<td>Powers et al.</td>
<td>Walking speed, stride length, cadence, GRFs (% body weight), ankle motion (*)</td>
<td>10 traumatic TT, 22–72</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Rao et al.</td>
<td>Walking speed; stride length (m); cadence, foot, shank, and thigh velocities (rad/s)</td>
<td>9 vascular TT, 62 ± 7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Schmalz et al.</td>
<td>Walking speed, stride length, $\text{VO}_2$ (mL/kg/m)</td>
<td>8 traumatic TT, 17–70</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Snyder et al.</td>
<td>Walking speed, stride length, cadence, GRFs (N/kg), ankle and knee motion (*)</td>
<td>7 vascular TT, 45–70</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Torburn et al.</td>
<td>Walking speed, cadence, stride length, EMG, $\text{VO}_2$ (mL/kg/min, mL/kg/m), joint motion (*)</td>
<td>5 TT (3 traumatic, 2 dysvascular), 43–58</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Torburn et al.</td>
<td>$\text{VO}_2$ (mL/kg/min, mL/kg/m), walking speed, stride length, cadence</td>
<td>10 traumatic TT, 51 ± 6, 7 vascular TT, 62 ± 8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
traumatic [2,3,13,56,67,76,81,83] or vascular transtibial amputees [13,22,66,71,81,83], and traumatic transfemoral amputees [57]. A few exceptions, however, were found. Compared to the SACH (Solid Ankle Cushion Heel) foot, three B-level studies found a higher self-selected walking speed with a prototype energy-storing foot in traumatic transtibial amputees [20] and with the Flex-Foot in traumatic [69] and vascular transtibial amputees [77]. Casillas et al. explained their results by the higher bioenergetic efficiency level the subjects experienced while walking with the prototype energy-storing foot [20]. Powers et al. and Snyder et al. both explained the observed difference in walking speed by the greater stride length with the Flex-Foot compared to the SACH foot [69,77], while cadence remained constant. Two studies reported a change in cadence. MacFarlane et al. found a lower cadence when individuals walked with the Flex-Foot compared to the SACH foot in combination with a greater stride length for the Flex-Foot [56]. Because of a trade-off effect, no differences were found in walking speed. Torburn et al. found a greater cadence for the Carbon Copy II foot compared with the Flex-Foot and SACH foot [81]. A possible explanation for the slightly different study results may be found in the differences in

Table 2.
Assessment of methodological aspects of reviewed studies on prosthetic knee, prosthetic socket, and prosthetic mass.*

<table>
<thead>
<tr>
<th>Author</th>
<th>Parameters</th>
<th>Subjects (Reason &amp; Level of Amputation, &amp; Age [yr] [Range])</th>
<th>Selection</th>
<th>Intervention</th>
<th>Statistical Validity</th>
<th>Total Score</th>
<th>Level of Evidence</th>
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</thead>
<tbody>
<tr>
<td>Board et al. [15]</td>
<td>Stump volume (mL), pistoning (cm), step length, stance duration</td>
<td>11 traumatic TT, 32–64</td>
<td>1 1 1 1 4</td>
<td>1 0 0 0 1 2</td>
<td>1 1 0 2 8</td>
<td>8</td>
<td>C</td>
</tr>
<tr>
<td>Boonstra et al. [17]</td>
<td>VO₂ (mL/kg/min, mL/kg/m), preference</td>
<td>28 traumatic/oncologic TF, 15–63</td>
<td>1 0 1 1 3</td>
<td>1 1 1 1 1 5</td>
<td>1 1 1 3 11</td>
<td>A</td>
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<tr>
<td>Boonstra et al. [18]</td>
<td>Walking distance, ease of walking, temporal variables, goniometry</td>
<td>28 traumatic/oncologic TF, 15–63</td>
<td>1 0 1 1 3</td>
<td>1 1 1 1 1 5</td>
<td>1 1 1 3 11</td>
<td>A</td>
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<tr>
<td>Czerniecki et al. [27]</td>
<td>VO₂ (mL/kg/m), walking speed</td>
<td>8 traumatic/oncologic TF, 30–44</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3 11</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Gailey et al. [35]</td>
<td>VO₂ (mL/kg/min)</td>
<td>10 traumatic/oncologic TT, 24–52</td>
<td>1 1 1 1 4</td>
<td>1 1 1 0 1 4</td>
<td>1 1 1 3 11</td>
<td>C</td>
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</tr>
<tr>
<td>Gitter et al. [37]</td>
<td>Muscle power output (W), joint power output (W)</td>
<td>8 traumatic/oncologic TF, 30–44</td>
<td>1 1 1 1 4</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3 11</td>
<td>B</td>
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<tr>
<td>Hale [39]</td>
<td>Walking speed, joint motion</td>
<td>6 traumatic/oncologic TF, 22–61</td>
<td>1 1 1 1 4</td>
<td>1 0 0 0 1 2</td>
<td>1 1 1 3 9</td>
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<td></td>
</tr>
<tr>
<td>Heller et al. [42]</td>
<td>Sway velocities (mm/s)</td>
<td>10 traumatic/oncologic TF, 38</td>
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<td>1 1 0 1 1 4</td>
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<td>B</td>
<td></td>
</tr>
<tr>
<td>Isakov et al. [46]</td>
<td>Heart rate, walking speed</td>
<td>14 vascular TF, 50–75</td>
<td>1 1 1 0 3</td>
<td>1 1 0 1 1 4</td>
<td>1 1 1 3 10</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Lehmann et al. [54]</td>
<td>Self-selected walking speed, VO₂ (mL/kg/m)</td>
<td>15 TT, 18–70</td>
<td>1 1 1 1 4</td>
<td>1 1 0 0 0 2</td>
<td>1 1 1 3 9</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Mattes et al. [59]</td>
<td>VO₂ (J/s), step length, swing time, stance time</td>
<td>6 traumatic/oncologic TF, 18–50</td>
<td>1 1 1 1 4</td>
<td>1 1 0 0 1 3</td>
<td>1 1 1 3 10</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Murray et al. [61]</td>
<td>Walking speed, stride length, cadence, temporal components of gait</td>
<td>7 traumatic TF, 33–46</td>
<td>1 1 1 0 3</td>
<td>1 0 0 1 1 3</td>
<td>1 1 1 3 9</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

*See main text “Methods” section for explanation of criteria and symbols, and see reference section for references.

Note: Criterion C12 (intention-to-treat) is not mentioned in this table, because this criterion was not applicable in all final-selected studies.

GRF = ground reaction force
TT = transtibial
TF = transfemoral
VO₂ = oxygen uptake
Table 3.
Main clinical findings of reviewed studies on prosthetic feet.*

<table>
<thead>
<tr>
<th>Author</th>
<th>Intervention</th>
<th>Outcome</th>
<th>Level of Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barth et al.</td>
<td>SACH foot, SAFE II, Seattle Lightfoot, Quantum, Carbon Copy II, Flex-Walk</td>
<td>Traumatic amputees: significantly shorter sound limb when wearing Flex-Walk and SAFE II; however, when wearing SACH, they had significantly longer sound-limb step length. Total group: with SACH foot, they had less dorsiflexion; with Flex-Walk, greater dorsiflexion than sound limb; with wearing Carbon Copy II and Quantum, greater sound limb acceptance forces. No significant differences in energy cost among prosthetic feet.</td>
<td>B</td>
</tr>
<tr>
<td>Boonstra et al.</td>
<td>Multiflex, Quantum</td>
<td>No differences in walking speed, plantar-dorsiflexion range of motion (ROM), knee joint ROM, hip flexion-extension ROM. Quantum foot: longer swing phase on prosthetic side, step time longer, inversion-eversion angle was 2.1° larger, adduction-abduction ROM was 3.1° larger.</td>
<td>B</td>
</tr>
<tr>
<td>Casillas et al.</td>
<td>SACH foot, energy-storing foot (prototype)</td>
<td>For traumatic amputees with energy-storing foot: free walking speed was higher, VO_{2} (per meter) was lower, more significant as speed increased. Higher satisfaction rating when amputees walked with energy-storing foot. No differences found for vascular patients.</td>
<td>B</td>
</tr>
<tr>
<td>Cortes et al.</td>
<td>SACH foot, Single Axis, Greissinger, Dynamic foot</td>
<td>Similar behavior for SACH and Dynamic feet (nonarticulated mechanism) on one hand and for Single Axis and Greissinger (articulated mechanism) on other hand.</td>
<td>B</td>
</tr>
<tr>
<td>Culham et al.</td>
<td>SACH foot, Single Axis</td>
<td>No differences in walking speed, cadence, stride length, gait cycle duration, mean peak stance phase flexion of prosthetic and contralateral limb. Angle of peak swing flexion was 46.37° ± 9.60° with SACH and differed significantly from Single Axis (41.34° ± 7.44°) in prosthetic limb; for contralateral limb, following angles were found: 51.35° ± 4.12° and 47.71° ± 7.10°.</td>
<td>B</td>
</tr>
<tr>
<td>Culham et al.</td>
<td>SACH foot, Single Axis</td>
<td>No differences of activity patterns or magnitude of knee and hip power outputs compared to SACH foot.</td>
<td>B</td>
</tr>
<tr>
<td>Doane and Holt</td>
<td>SACH foot, Single Axis</td>
<td>No differences in velocity of center of mass. SACH foot: ankle angle of prosthetic leg during foot-flat was less than with Single Axis foot (~5.4 ± 2.1° and –11.9 ± 3.0°, respectively).</td>
<td>B</td>
</tr>
<tr>
<td>Gitter et al.</td>
<td>SACH foot, Seattle Foot, Flex-Foot</td>
<td>Seattle and Flex-Foot: increase in energy absorption and release during push-off, but no differences in pattern or magnitude of knee and hip power outputs compared to SACH foot.</td>
<td>B</td>
</tr>
<tr>
<td>Goh et al.</td>
<td>SACH foot, uniaxial foot</td>
<td>No differences in walking speed. SACH foot: period of heel-strike to foot-flat of prosthetic leg took twice as long as that of uniaxial foot for transfibial and transfemoral amputees (44.5% vs. 22.4% and 33.7% vs. 20.4%, respectively). Transfibial and transfemoral showed an average difference of 7.5° and 5.0°, respectively, in ankle angle during early-stance phase. No differences in GRFs for transfibial amputees. Vertical GRF on prosthetic side for transfemoral amputees showed differences in its loading pattern: SACH foot has two-peak loading pattern, uniaxial a three-peak loading pattern.</td>
<td>C</td>
</tr>
<tr>
<td>Hsu et al.</td>
<td>SACH foot, Flex-Foot, Re-Flex VSP</td>
<td>Improvements of Re-Flex VSP vs. Flex-Foot and SACH foot: energy cost—walking 5% and running 11%, gait efficiency—walking 6% and running 9%. No differences between Flex-Foot and SACH foot.</td>
<td>B</td>
</tr>
<tr>
<td>Huang et al.</td>
<td>SACH foot, Single Axis, Multiple Axis</td>
<td>No differences in energy consumption. SACH foot: good late-stance stability, limited dorsiflexion. Multiple Axis foot: less late-stance stability, more late-stance dorsiflexion. Ankle joint degree of freedom is an important factor for comfort; Multiple Axis most comfortable.</td>
<td>B</td>
</tr>
<tr>
<td>Lehmann et al.</td>
<td>SACH foot, Seattle Foot, Flex-Foot</td>
<td>No differences in walking speed, and metabolic efficiency during walking and running. Flex-Foot: longest midstance phase, greatest ankle range angle, and greater forward movement of center of pressure.</td>
<td>C</td>
</tr>
<tr>
<td>Lehmann et al.</td>
<td>SACH foot, Seattle Foot</td>
<td>No differences in walking speed and in metabolic efficiency during walking and running. Seattle Foot: longer midstance phase, push-off phase was shorter, ankle ROM during stance was greater (20.2° vs. 9.8°), maximal dorsiflexion moment was greater (97.5 Nm vs. 84.3 Nm), knee ROM during stance was greater (43.2° vs. 34.3°), knee ROM during swing was greater (66.0° vs. 62.1°).</td>
<td>C</td>
</tr>
<tr>
<td>MacFarlane et al.</td>
<td>Conventional foot, Flex-Foot</td>
<td>Walking with conventional foot was more difficult across all grade and speed conditions.</td>
<td>B</td>
</tr>
<tr>
<td>MacFarlane et al.</td>
<td>Conventional foot, Flex-Foot</td>
<td>No differences in walking speed. Flex-Foot: stride length increased (134.3 cm compared to 129.8 cm) and cadence decreased; single support time increased, allowing larger, more normal steps with uninvolved leg, which means decrease of cadence, reflected by increase in cycle time (124.3 for Flex-Foot and 122.2 for conventional foot).</td>
<td>B</td>
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</table>
the selection of the study groups. In two B-level studies, MacFarlane et al. reported a more symmetrical gait pattern with the Flex-Foot compared to a SACH foot in both transtibial and transfemoral amputees related to symmetrization of the late stance and late swing phase durations in particular [56,57].

Some studies investigated joint motion as an outcome parameter [13,16,22,45,52,53,66,67,69,77,81]. In the A-level study by Postema et al. [67], the range of motion (ROM) at the ankle during the stance phase of a single-axis conventional foot was greater than the same ROM of two energy-storing feet. This result could readily
be related to the mechanical characteristics of the different feet, i.e., the presence or absence of an ankle axis in the frontal plane. The presence of an ankle axis allowed greater early-stance plantar flexion immediately after heel contact \cite{66, 67}. Furthermore, the energy-storing Flex-Foot showed a greater late-stance dorsiflexion compared with the conventional SACH foot in three B-level studies \cite{69, 77, 81} and two C-level studies \cite{52, 76} on traumatic and vascular transtibial amputees. The fact that the Flex-Foot resulted in a greater stride length indicates a greater tibial advancement as a result of increased dorsiflexion \cite{77}.

Nine B-level studies assessed oxygen consumption \cite{13, 20, 44, 45, 52, 58, 76, 81, 83}. In three studies with traumatic transtibial amputees, oxygen consumption per distance traveled was slightly lower with a prototype
energy-storing foot [20] or with the Flex-Foot [58,63] than with the SACH foot. In the study of Hsu et al. with nonvascular amputees, oxygen consumption was lower with the Re-Flex VSP compared with the SACH and Flex-Foot [44]. However, in the other six studies no such beneficial effect of energy-storing feet was found [13,45,52,76,81,83]. This discrepancy in results, however, is hardly clinically significant and may again be related to differences in the selection of the study groups.

As for patient satisfaction, the only A-level study concluded that no specific prosthetic foot was consistently favored over another type of foot by traumatic transtibial amputees [68]. Yet, in one B-level study, the prototype energy-storing foot scored a higher satisfaction rate than the SACH foot in traumatic transtibial amputees [20]. Another B-level study concluded that walking with the SACH foot was perceived to be more difficult than walking with the Flex-Foot [56]. However, since the prosthetic users were not blinded in the latter two studies, these results should be interpreted with caution.

**Studies on Prosthetic Knees**

Each of the five studies on prosthetic knees made different comparisons (Table 4). The A-level study of Boonstra et al. concluded that a Tehlin knee with a pneumatic swing phase controller resulted in a more comfortable and faster walking performance during normal and fast walking compared to a knee with a mechanical swing phase control, i.e., Otto Bock 3R20 (results from questionnaires) [18]. This result was explained by a shorter swing phase duration of the prosthetic leg caused by an impeded knee flexion. However, energy expenditure at 3 km/h was somewhat higher with the pneumatically controlled knee [17]. Apparently, the preference of the amputees in favor of the Tehlin knee was not related to lower energy costs. Similar results were found in two B-level studies. Heller et al. found that a conventional knee unit resulted in a more comfortable and faster walking speed during normal and fast walking. Because of the better fit, the amputees spent more time on their prosthetic limb and felt more confident of the control over and position of their prosthesis. The improvements in the smoothness of walking are most likely related to the restraining effect of the hydraulic or pneumatic component at the beginning and the end of the prosthetic swing phase, allowing more normal weight acceptance at the beginning of the prosthetic stance phase and easier weight transfer at the end of prosthetic stance phase [61]. On the other hand, the B-level study of Isakov et al. [46] concluded that a Mauch S-N-S hydraulic knee prosthesis with a locked knee may enable vascular patients to adopt a higher walking speed compared to an unlocked open-knee unit. This finding should be interpreted in view of the fact that their study sample was characterized by an older age (50–70 years) and a lower activity level (i.e., vascular amputees with additional health problems, such as diabetes mellitus, hypertension, heart failure, and myocardial infarction) compared to the studies of Boonstra et al. [17,18] and Heller et al. [42].

**Study on Prosthetic Socket**

Board et al.’s C-level study investigated the effect of prosthetic socket type on time-distance parameters in transtibial amputees [15] (Table 4). More symmetrical step length and stance duration and less stump volume loss were observed with a vacuum total surface-bearing suction socket compared to a normal total surface-bearing suction socket. This result can be explained by the assumption that a vacuum socket provides a better fitting of the stump tissues and a better “total skin” contact, allowing more mechanical and sensory control over the prosthetic leg. The subjects reported that their prosthetic limb was held more firmly with the vacuum socket and that their stump pistoned less within the socket during walking. Because of the better fit, the amputees spent more time on their prosthetic limb and felt more confident of the control over and position of their prosthesis. The methodological quality of this study was poor, however, because the other prosthetic components were not kept constant with the different sockets. Also the time to adapt to the prosthetic change was relatively short, i.e., subjects were familiarized with the intervention for only 15 minutes. Therefore, the results of this study should be interpreted with caution.

**Studies on Prosthetic Mass**

The six studies on prosthetic mass (Table 4) did not reveal any influence of mass on the efficiency or
kneel flexion requires a greater arc of functionally et al., the stability of timely foot-flat support with limited transfer onto their prosthesis [1,66,67]. According to Perry from an early foot-flat mechanism to facilitate weight especially the more inactive prosthetic users may benefit early-stance-phase stability. Some researchers believe that a conventional SACH foot in both traumatic and vascular plane, allowing an early foot-flat position and concomitant roll-off motion of the ankle-foot complex in the sagittal plane, mimicking the normal roll-off motion of the ankle-foot complex in the sagittal plane, allowing an early foot-flat position and concomitant early-stance-phase stability. Some researchers believe that especially the more inactive prosthetic users may benefit from an early foot-flat mechanism to facilitate weight transfer onto their prosthesis [1,66,67]. According to Perry et al., the stability of timely foot-flat support with limited knee flexion requires a greater arc of functionally restrained plantar flexion [66]. Also, uphill and downhill walking may be easier with a wide ROM at the prosthetic ankle joint [58]. A single-axis foot, however, may offer relatively little late-stance stability because of an unrestrained dorsiflexion [66]. In this respect, the Flex-Foot and the SACH foot provide more stability during the late-stance phase [45] and may be preferable to patients who tend toward a short prosthetic stance phase. Hence, individual considerations related to intended use and activity level remain important with respect to the definitive choice of the prosthetic foot. One should note that in the reviewed studies, dorsiflexion is also used for the prosthetic feet that have rigid ankles. This can be confusing because they do not truly dorsiflex, but bend. Therefore, pseudo-dorsiflexion could be more appropriate when one is discussing the properties of rigid ankles.

As for the prosthetic knee in transfemoral amputees, one can conclude that a prosthesis with an advanced mode of swing-phase control, either by a pneumatic or a hydraulic knee unit, is somewhat superior to a prosthetic knee that only provides a constant force or friction. Especially active prosthetic users may profit from the advanced characteristics of swing-phase controllers, such as the Tehlin knee, in terms of gait symmetry and comfortable walking speed [42,61]. These beneficial effects cannot readily be explained on the basis of energy expenditure. On the other hand, the typical geriatric vascular patient may still profit from the stance-phase stability that is provided by a conventional locked-knee unit [46]. To what extent prosthetic knees with stance-phase stabilizers such as the Intelligent Prosthetic Knee should be prescribed to these or other patients based on its functional benefits has to be further supported by clinical evidence. Hence, again, individual considerations must ultimately determine the choice and prescription of the prosthetic knee.

With regard to the prosthetic socket used by transtibial amputees, firm conclusions cannot be drawn from the literature. It is, nevertheless, plausible from a clinical perspective that a vacuum (total-surface bearing) socket assures a better skin contact than a normal suction or suspension socket and, thus, a better control over the prosthetic limb [14]. Within certain limits, prosthetic mass does not seem to influence the gait pattern or efficiency in lower-limb amputees. However, there is some evidence that a proximal center of mass location results in a slightly more efficient gait than a distal distribution of prosthetic mass [54].

Functional outcomes should be assessed for various aspects of mobility, such as making transfers, maintaining balance, walking level, climbing stairs, negotiating ramps and obstacles, changing walking speed, etc. Most studies reviewed in this paper assessed walking on a treadmill (at self-selected walking speeds), probably for reasons of technical and practical convenience. Indeed, Mulder et al. already pointed out that the vast majority of clinical studies...
on human walking have used rather standardized gait assessment protocols with limited “ecological validity” [90]. Although perhaps less analytic, modern systems for ambulatory monitoring of human activity [91] can provide objective and valid data about (changes in) human motor behavior during prolonged periods of hours or days in a much more ecologically valid way. First, subjective assessments of comfort, stability, and efficiency should certainly be used more when blinding of the prosthetic users can be assured. Second, the effects of different prosthetic feet should also be evaluated in patients with, for example, a through-knee or transfemoral amputation because generalizing results from transtibial amputees to these higher levels of amputation may be invalid. Last, more research is needed into the effects of prosthetic knees with stance-phase stabilizers as well as into the functional effects of different prosthetic sockets in through-knee and transfemoral amputees.

Therefore, with regard to prosthetic guideline development, we must still largely rely on clinical consensus among experts. In a formal consensus procedure, different sources of evidence are needed.

CONCLUSION

Our formal clinical knowledge has considerable gaps concerning the (beneficial) effects of different prosthetic components on human functioning with a lower-limb prosthesis. For future research, functional comparisons between different prosthetic components should be categorized according to the level of activity of the amputee and the intended use of the prosthesis. Such an approach would better acknowledge the importance of individual needs and abilities that guide clinical decision-making in daily practice. The integration of knowledge from research with the expert opinion of clinical professionals and the opinions and wishes of consumers can form a solid base for a procedure on guideline development for prosthetic prescription.

REFERENCES

16. Boonstra AM, Fidler V, Spits GM, Tuil P, Hof AL. Comparison of gait using a Multiflex foot versus a Quantum


Appendix: Methodological Criteria

Selection of Patients

A1, Adequacy of Description of Inclusion and Exclusion Criteria: This criterion tested whether the patient sample was sufficiently defined with the use selection criteria: such as age, gender, level of amputation, reason for amputation, activity level of the amputee, time since onset, stump condition, and comorbidity.

A2, Functional Homogeneity: The homogeneity of the study sample was assessed for all study designs. In view of clinical guideline development, at least the activity level of the included subjects should be reasonably equal. When the activity level of the patients was not described, sufficient indication of the level of amputation, the reason for amputation, and the age of the subjects were required to globally estimate the activity level of the patients. If the study sample was heterogeneous, a stratified analysis of the outcome was required to obtain a “1” score.

A3, Prognostic Comparability: As for group designs, the study groups should be comparable for possible confounding factors, such as time since onset and time since first walking with the prosthesis. In the case of a within-subjects design, this criterion was scored “1.”

A4, Randomization: In group designs, an adequate randomization procedure should have been applied. If the randomization procedure was described and the procedure reasonably excluded bias, this criterion was scored as “1.” In within-subjects designs, this criterion was applied to the sequence of interventions [1].

Intervention and Assessment

B5, Experimental Intervention: The experimental intervention had to be given explicitly in such detail as to make performing a duplicate study as described possible.

B6, Cointerventions: This criterion tested whether cointerventions were avoided or were comparable between the study groups.

B7, Blinding: In any case, the outcome assessor had to be blinded to the intervention. In many studies investigating prosthetic components, blinding of the patients is always difficult to assure. Therefore, this type of blinding was required only for studies using subjective outcome measures.

B8, Timing of the Measurement: This criterion pertained to the moment that the outcome was assessed in relation to the time period subjects were given to adapt to the prosthetic change. An adequate adaptation period was required. According to English et al., transfemoral amputees need at least 3 weeks of walking with a new knee
mechanism to be sure that gait parameters are stable [2]. Also according to English’s results and based on clinical experience [2], the amputees are assumed to need a period of at least 1 week to adapt to a new prosthetic foot or to a change in prosthetic mass.

B9, Outcome Measures: The outcome parameters should be adequate in relation to the purpose of the study, and they should have been collected with the use of a standardized protocol.

Statistical validity:

C10, Dropouts: The number of dropouts and the reason for dropping out had to be sufficiently reported. A dropout rate of more than 20% was considered as insufficient.

C11, Sample Size: The sample size \(n\) in relation to the number of independent variables \(K\) was adequate if the ratio \(n:K\) exceeded 10:1.

C12, Intention to Treat: Intention to treat analysis should be assessed in the case of dropouts.

C13, Data Presentation: This criterion required that adequate point estimates and measures of variability were presented for the primary outcome measures.