Mobile application for tracking lower limb amputee fitness

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In 2005, there were an estimated 1.6 million amputees living in the United States and approximately 185,000 Americans become new amputees each year. The total number of amputees is projected to double by 2050 (Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008). The incidence of amputation due to diabetes and other dysvascular conditions is increasing by approximately 3% annually, with the total number of amputees projected to double by 2050 (Dillingham, Pezzin, & MacKenzie, 2002; Ziegler-Graham et al., 2008). As these trends continue, amputees will represent a significant part of the patient population. Healthcare professionals must be certain to consider the unique physiology of amputee patients when formulating treatment plans, setting goals, and creating wellness regimens.

The vast majority (>80%) of amputations are the result of peripheral vascular disease. Amputees often exhibit comorbidities such as diabetes, cardiovascular dysfunction, and obesity that adversely impact their overall health. Cardiovascular disease is the primary cause of death for amputees, with prevalence rates as high as 75%. A study by Frugoli et al. (2000) found that amputees also exhibit higher rates of hypertension, diabetes, and high cholesterol than non-amputees. The authors stressed that amputees should pursue cardiovascular disease prevention programs in order to reduce their risk. Amputees are also at a greater risk for osteoarthritis, joint pain, back pain, and osteoporosis due to gait deviations, unequal limb usage, and other factors regardless of etiology (Gailey, Allen, Castles, Kucharik, & Roeder, 2008).

Excess body weight is a contributing factor for all of these health concerns. More than 65% of Americans are overweight or obese, and amputees are no exception (Donnelly et al., 2009). A prospective study of 1.46 million Caucasian adults (160,087 deaths) found that obesity
and overweight were associated with a higher mortality rate than optimal or underweight subjects (Berrington de Gonzalez et al., 2010.) Mortality rates were lowest for subjects with a body mass index of 20-24.9 (optimal). Conversely, weight loss or maintenance is associated with numerous benefits including: “an improvement in CVD risk factors such as decreased blood pressure, decreased LDL-C, increased HDL-C, decreased triglycerides (TG), and improved glucose tolerance. Weight loss has also been associated with a decrease in inflammatory markers, such as Creactive protein, which have also been associated with the development of CVD” (Donnelly et al., 2009).

Littman et al. (2015) conducted a retrospective study of weight changes for 759 male lower limb amputees. The researchers collected body weight data from amputees and age-matched controls. Compared with the initial baseline, data from 39 months post-amputation were higher for men with amputation than without. Transfemoral and transtibial amputees gained an average of 8-9%, partial foot amputees gained 3-6%. Compared with non-amputees, transfemoral and transtibial amputees were five times as likely to gain more than 10% over 39 months. Obesity can lead to difficulties with prosthetic treatment by drastically limiting prosthetic component options and causing problems with fit and suspension. Excess tissue can be difficult to contain within the socket and may decrease the efficacy of suspension systems (Kahle & Highsmith, 2008).

Due to their altered anatomy and biomechanics, amputees must consider weight control, muscle strength, joint health, and cardiovascular fitness as crucial parts of their overall wellness (Kahle & Highsmith, 2008). According to exercise management guidelines from the American College of Sports Medicine: “Therapeutic exercise for LE amputations that incorporates the involved extremity should be performed for cardiovascular endurance, muscular strength, and
endurance, and for ROM, proprioception, and balance”. When referring to treatment plans for amputees, the authors reiterate:

The main purpose of exercise management for vascular amputees is to preclude or abate the pathogenesis of diabetes, atherosclerosis, or both...exercise management for nonvascular LL amputees is similar to that for nondisabled persons. That is, exercise management focuses on risk reduction for developing secondary disabilities such as cardiovascular disease, diabetes, high blood pressure, and obesity (Pitetti & Pedrotty, 2009).

Physical activity has many benefits for amputees including: improved cardiovascular health, increased muscle force, and decreased body mass. Higher activity level and functional prosthetic use are positively associated with higher patient satisfaction and frequency of prosthesis use (Agrawal, Skrabek, Embil, Gross, & Trepman, 2014). Additionally, “rehabilitation time of individuals with limb amputations [is] shorter when physical training [is] part of their rehabilitation programme” (Bragaru, Dekker, Geertzen, & Dijkstra, 2011). Littman et al. (2015) agree, adding “weight loss interventions should target individuals soon after they have recovered from their amputation, to prevent weight gain and to ensure healthy habits are learned and maintained”.

It is important to note that energy expenditure is significantly increased for amputees compared to non-amputees, with more proximal amputations requiring more energy for walking (Waters, Perry, Antonelli, & Hislop, 1976; Pinzur, Gold, Schwartz, & Gross, 1992; Nowroozi, Salvanelli, & Gerber 1983; Bell, Wolf, Schnall, Tis, & Potter, 2014; Gonzalez, Corcoran, & Reyes, 1974). Amputee gait differs from “normal” gait as a result of anatomical changes, compensatory mechanisms, and the integration of mechanical prosthetic components. For example, transfemoral amputees demonstrate up to 54% slower self-selected walking speed compared with normal subjects while increasing stance phase for the intact limb (Waters et al., 1976; Pinzur et al., 1992; Jaegers, Arendzen, & de Jongh, 1995;). Atrophy of hip musculature,
reduced knee extension/flexion control, and lack of ankle motion contribute to gait deviations for transfemoral amputees. In addition to decreased gait velocity and symmetry, deviations can include: lateral trunk bending, knee instability, abnormal heel rise, circumduction, or vaulting. For transtibial patients, loss of proprioception, balance, and control of ankle joint motion contribute to gait changes that require more energy. These can include: asymmetric gait, abnormal knee motion, and drop off. Transtibial amputees walk significantly slower than normal subjects, likely due to lack of propulsion at the ankle (Czerniecki, 2002). Prosthetic alignment can also impact amputee gait and energy expenditure. For instance, excessive ankle plantarflexion can cause a transtibial amputee to hyperextend at the knee, making second rocker difficult to initiate. The patient may use increased hip flexion or other compensatory mechanisms to ambulate “normally” while sacrificing efficiency.

This increased energy requirement for walking is an important consideration for amputees as they work to safely maintain a healthy weight, particularly for those who have comorbidities. In order to create fitness regimens that are safe for amputees with diabetes, cardiovascular disease, and other conditions, knowledge of caloric output is critical. Determining caloric needs (both intake and output) for amputees is vital for formulating and adhering to weight control programs as well. For amputees who are physically fit and undergoing strenuous training programs, accurate knowledge of calorie balance is necessary to avoid malnourishment.

Activity and calorie tracking can serve as an important tool for those attempting to follow a fitness regimen. Carels et al. (2005) performed one of the only studies on the relationship between self-monitoring and weight loss outcomes. They found that among obese subjects, self-monitoring (paper diary) of physical activity yielded greater weight loss and increased weekly exercise compared with subjects who did not record their progress. Additionally, those who
consistently monitored their physical activity lost nearly twice the weight and exercised twice as often as those who kept inconsistent records.

In recent years, there has been an increase in health-related applications (“apps”) for cellular phones that serve as tools for self-monitoring. A review of mobile health apps found that, in general, app users have increased physical activity levels. “Each study contributed to the body of evidence supporting the role of self-monitoring; more frequent self-monitoring was consistently and significantly associated with weight loss compared to less frequent self-monitoring” (Burke, Wang, & Sevick, 2011). A study that compared digital versus paper self-monitoring methods found those who used a PDA program (similar to an app) had more success than subjects who used a paper diary to track physical activity. During the six month study period, subjects that self-monitored their daily activities showed higher physical activity levels and weight loss than those who did not. Moreover, subjects who used a PDA were more consistent and maintained a journal longer than those who used a paper diary (Conroy et al., 2011).

Littman et al. (2015) conducted a large survey of veteran amputees that focused on body mass index and weight loss strategies. After calculating limb loss adjusted body mass index, the authors found that 23% of respondents were normal weight, while 76% were overweight or obese. When asked about their weight loss strategies, “83% of those trying to lose weight reported trying to ‘eat differently’, but only 7% were following a comprehensive weight loss program involving dietary changes, physical activity, and behavioral counseling”. They also found that while 53.5% of subjects were using physical activity as a part of their weight loss strategy, only 5.6% used journaling/recording to track their progress.
The amputee population is largely overlooked in terms of fitness and weight control programs. Despite the proven disparity in caloric needs, there are no tools on the market for calculating and recording energy expenditure for amputees. An internet search yielded a single website, called TouchCalc, which included a body mass index calculator for amputees, though no further interpretation or information was provided (Fadem, 2008). Current nutrition guidelines for diéticians include calculations for modification of caloric intake for amputees; however, an extensive search yielded no results for modified calorie expenditure tables (Piland & Adams, 2009). Textbooks on exercise physiology or nutrition often include a chapter on amputees without addressing the need for caloric adjustments for intake or output (Pitetti & Manske, 2004; Charney & Malone, 2008; American College of Sports Medicine, 2009). The Veterans Association produced a 240+ page manual for amputee training, exercising, and muscle conditioning, yet calorie balance is never mentioned (Burgess & Rappoport, 1993). There is a need for a user-friendly, accurate, and accessible tool for amputees to track their physical activities and caloric balance. The purpose of the project is to design a framework for a mobile application (“app” for cellular phones, tablets, etc) which would provide estimated caloric expenditures for lower limb amputees while walking. A review of the current literature on amputee energy expenditure will be used to create the prototype and substantiate the need for such a tool.

Methods

The literature used for the project was acquired through the libraries of Eastern Michigan University and Central Michigan University. Additional resources were located using internet search engines, reference lists of relevant articles, and the author’s personal library. Searches were performed in stages based on the following categories: amputee health and risk factors,
amputee energy expenditure, body mass index/weight, dietetics protocols, factors influencing amputee gait parameters, factors influencing quality of life, and demographic data. Papers were excluded from review if the samples were not representative of the patient population (e.g. too specific, such as Cambodian landmine victims). A secondary search was performed to locate resources relating to efficacy of fitness applications, factors contributing to successful weight loss programs, and the benefits of exercise for amputees.

The resources related to body mass index, energy expenditure, and dietetics were used to create formulas for estimating calorie balance for amputees. The formulas included estimated caloric intake requirements and caloric output values for walking. Several formulas for “corrected” body mass index were evaluated using Microsoft Excel to determine inclusion. A table was created using sample height and weight values. Each formula was applied to the table and the resulting body mass index values were compared. Finally, a modified formula for calculating ideal body weight was evaluated using a similar method.

The resources related to energy expenditure were used to establish average caloric requirements based on amputation level. These averages were integrated into existing formulas for caloric output based on weight in order to establish estimated values for amputees. Microsoft Excel was used to verify accuracy of the formulas as well as create modified caloric output charts.

Finally, the resources related to mobile application use and weight loss programs were used to establish parameters for a hypothetical fitness application. A wireframe prototype application interface was created using Invision software (www.invisionapp.com). The prototype was built to demonstrate the interface only using a single data set. Coding and creation of a functional program may be pursued in the future.
Results

A number of studies have been performed to determine the energy requirements of walking for lower limb amputees. It is often difficult to compare results between studies due to variations in population, sample demographics, methods, and reporting of results. For the purposes of this project, several studies will be analyzed and compared where possible to establish reasonable energy expenditure values for the application. Oxygen consumption serves as a proxy for energy (calorie) expenditure and can be easily measured using specialized equipment. When possible, oxygen consumption data will be standardized by calculating oxygen used per kilogram per meter travelled (work). This allows for some comparison between studies regardless of walking velocity or patient weight. The preeminent text in the field of prosthetics is the *Atlas of Amputations and Limb Deficiencies* (Smith, Michael, & Bowker, 2004). In the chapter on energy expenditure, the authors focus on data collected from Waters et al. (1976) and Nowrozzi et al. (1983). In addition to these, several other notable studies will be evaluated as a sampling of available literature.

A study by Waters et al. (1976) is regarded by many as the seminal work on energy expenditure of amputees. The researchers studied oxygen consumption in 50 normal subjects and 70 unilateral amputee subjects. The participants walked around a track at their self-selected speed for one trial and then walked as fast as possible for the second trial. Waters et al. found that walking velocity was consistent for normal subjects, regardless of age. For amputees, velocity was significantly decreased (13-66%) compared to normal values and depended on both amputation level and cause. Traumatic amputees walked faster than vascular amputees; higher level amputees walked more slowly than lower level subjects. In order to standardize the oxygen consumption data, the researchers calculated the energy cost per meter (mL O₂/kg-m). They note
this is “the best way to compare the gait efficiency at different amputation levels”. When compared with normal values, the results were as follows:

<table>
<thead>
<tr>
<th>Amputation</th>
<th>Energy Expenditure vs. Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vascular, Transfemoral</td>
<td>+121%</td>
</tr>
<tr>
<td>Vascular, Transtibial</td>
<td>+64%</td>
</tr>
<tr>
<td>Vascular, Symes</td>
<td>+34%</td>
</tr>
<tr>
<td>Traumatic, Transfemoral</td>
<td>+56%</td>
</tr>
<tr>
<td>Traumatic, Transtibial</td>
<td>+38%</td>
</tr>
</tbody>
</table>

Based on their raw data, the authors concluded that amputees demonstrate normal levels of oxygen use at their comfortable walking speed. When the data are standardized as energy cost per meter walked, amputees use significantly more energy to ambulate than able-bodied subjects. The results suggest that amputees modify their walking speed in order to keep energy costs low. The authors also found that amputees utilized a normal proportion of their maximum aerobic capacity to walk at a comfortable rate. For example, a normal subject in their 60s used 41% of their capacity, while the average vascular transtibial patient used 42%. The exception to this pattern were the vascular transfemoral subjects, who used 63% of their aerobic capacity for comfortable walking.

Overall, the study by Waters et al. (1976) was well-executed, with thoroughly documented and replicable methods. The authors avoided making modifications to the prostheses and instructed subjects walk on a track rather than a treadmill to avoid influencing their normal gait patterns. The large sample size (n=120) is rare in the field of prosthetics and helps improve the quality of the study. Finally, Waters et al. approached their data from several angles in order to better understand the energy demands of amputees in a way that is clinically relevant. By standardizing the data and removing the velocity variable, they made it easy to directly compare
their study with other research. It should be noted, however, that when Waters and Mulroy (2004) refer to the data from this particular study in the *Atlas of Amputations and Limb Deficiencies*, the numbers are different. Using the data provided in the textbook, the numbers in the table above become much lower (87%, 33%, 13%, 33%, and 7% respectively). A thorough search yielded no redactions or corrections to the 1976 paper, though a review paper by Waters and Mulroy (1999) also utilizes the lower numbers. The 1999 paper presents the data in relation to data from Nowrozzi et al. (1983) for hip disarticulation and hemipelvectomy subjects. Perhaps Waters and Mulroy chose to alter the 1976 data set to better align with the data from Nowrozzi et al.; the alternate data set does fall within one standard deviation of the original data set.

Nowrozzi et al. (1983) performed a similar experiment using eight hip disarticulation (HD) amputees, ten hemipelvectomy (hp) amputees, and 11 control subjects. The amputees walked on a track at comfortable, fast, and slow walking speeds while oxygen consumption data were collected. The controls performed one trial at their comfortable speed. The data collected showed that the amputees walked significantly slower than the controls; the “fast” speed for amputees was still slower than the comfortable speed for the controls. There was no significant difference in speeds between HD and hp subjects, though the HD patients did walk somewhat faster on average. The oxygen consumption data were similar to Waters et al. (1976). While the oxygen usage per minute was not significantly different between amputees and controls, the consumption per meter was significantly higher for the amputees. The comfortable walking speed for HD subjects was only 61% of the controls’ speed and their oxygen consumption per meter was 80% higher; the hp patients walked at 51% of the controls’ speed and used 122% more oxygen per meter. Finally, the subjects performed a trial using swing-though gait on crutches with no prosthesis. The HD and hp patients demonstrated speeds faster than their
comfortable walking speed, as well as oxygen consumption only 45% greater than the controls. A study of transtibial patients found the opposite correlation: amputees used 43% more oxygen when using crutches versus a prosthesis (Pagliarulo, Waters, & Hislop, 1979). The discrepancy likely reflects the difference in effort required to operate a prosthesis which replaces one joint (transtibial) as opposed to three joints (HD).

The study performed by Nowrozzi et al. (1983) paralleled that of Waters et al. (1976), albeit on a smaller scale. The researchers minimized alterations to the patients’ gait by performing trials on a smooth, indoor surface with their own prostheses. The sample size is much lower in this study, though this is not uncommon in prosthetic experiments, especially with high level amputees. The patients were also notably younger in this experiment, likely due to the nature of high level amputations (typically cancer-related). While Nowrozzi et al. did not exactly duplicate the methodology of previous study, enough similarity exists between the experiments to be able to compare the results directly. One aspect of the design which may have negatively impacted the results was the number of trials performed. Nowrozzi et al. had the patients perform a “test run”, three walking trials, and one crutch trial, each separated by a 30 minute rest period. Undergoing over three hours of testing may have become tiresome for the subjects and influenced some of the later trials. It should be noted, however, that the final trial (using crutches) resulted in the lowest energy expenditure for both HD and hp amputees.

Pinzur et al. (1992) performed a study examining the energy expenditure of several amputation levels, similar to Waters et al. (1976). Unlike previous studies, they sampled only dysvascular amputees in order to encompass the largest demographic, as over 80% of lower limb amputations are related to vascular disease. The researchers were particularly interested in determining how much of the subjects’ aerobic capacity was required for comfortable walking
and fast walking. The sample consisted of 25 dysvascular amputees: five each of midfoot, Syme’s, transtibial, knee disarticulation, and transfemoral. The controls were five age-matched non-amputees with a history of vascular disease. The subjects’ comfortable walking speed was determined by walking in a hallway and duplicated on a treadmill for the actual trials. Pinzur et al. concluded that amputees used more of their aerobic capacity (70-80%) for normal ambulation than the controls (65%). Both groups exhibited markedly higher results than in a previous study of non-dysvascular patients (Waters et al., 1976). The study did not provide oxygen consumption per meter, though enough data were provided to perform the calculations manually. The results were as follows:

<table>
<thead>
<tr>
<th>Amputation</th>
<th>Energy Expenditure vs. Dysvascular Controls</th>
<th>Energy Expenditure vs. Healthy Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midfoot</td>
<td>+16% [-0.6%]</td>
<td>+27%</td>
</tr>
<tr>
<td>Syme’s</td>
<td>-5%</td>
<td>+21%</td>
</tr>
<tr>
<td>Transtibial</td>
<td>+12%</td>
<td>+44%</td>
</tr>
<tr>
<td>Knee Disarticulation</td>
<td>+55%</td>
<td>+98%</td>
</tr>
<tr>
<td>Transfemoral</td>
<td>+54%</td>
<td>+97%</td>
</tr>
</tbody>
</table>

Of particular note are the midfoot and Syme’s results, which deviate from the expected pattern. Close examination of the data provided in the article reveals a mathematical error in the oxygen consumption calculation for the midfoot amputees. The oxygen consumption per meter can be calculated by dividing the oxygen consumption per minute by the velocity. The researchers have listed this number as 0.237, though a manual calculation yields a value of 0.2037. One might assume the researchers made a keystroke error in the article, however all of the subsequent tables, graphs, and charts include this erroneous data point. When this error is corrected, the energy expenditure is shown to have decreased by 0.6% compared to the controls. Considering that the walking speeds in this study are already well below those of healthy adults,
it is not unreasonable to conclude that midfoot amputation had little or no impact on energy expenditure. The patients and controls in this study were likely not relying on the third rocker for propulsion, regardless of amputation level. The Symes amputees demonstrated an unexpected decrease in energy expenditure compared with the controls. It is important to again consider the physical condition of the control patients in this study. A comparison of the Symes patients to healthy adults from other studies results in a 21% increase in oxygen consumption. The patients in Pinzur et al.’s study may have actually benefited from the amputation by replacing a neuropathic, weakened foot with a functional, rigid lever (prosthesis). Finally, conflicting research exists about the influence of treadmill walking on gait patterns, so the impact of this experimental design choice is not known (Traballesi, Porcacchia, Averna, & Brunelli, 2008). It would therefore be difficult to directly compare the results with those of Waters et al. (1976) without understanding the potential ramifications of treadmill use.

A well-known study by Gonzalez, Corcoran, and Reyes (1974) compared the energy needs of transtibial amputees in relation to residual limb length. The researchers separated the nine male participants into a “short” limb group (less than 6% of total body height) and a “long” limb group (more than 8% of total body height). The subjects completed a total of six walking trials at comfortable, fast, and slow speeds down a level hallway. The results showed no significant correlation between residual limb length and comfortable walking speed. Oxygen consumption per meter was calculated for various speeds and revealed an average increase of 10% for long limbs and 40% for short limbs compared to normal values. As in previous studies, the authors note that there was no significant difference in oxygen consumption at comfortable walking speed between groups, though the amputees’ comfortable walking speed was 22% lower than normal values. Researchers also found a correlation coefficient of -0.74 when they graphed the
percent increase in oxygen consumption versus residual limb length. They concluded that limb length does impact energy expenditure and should be considered before surgery. “Even a short-stump BK amputation with a stump length sufficient to be fitted with a regular prosthesis would mean a great reduction in energy expenditure compare to that at an AK level. Amputation at an optimal BK stump length for all practical purposes causes minimal rise in work load”.

The study by Gonzalez et al. (1974) has several positive and negative aspects which could impact the quality of the results. The authors chose to include various etiologies, presumably to create a representative sample of amputees. The small sample size limits the applicability of the results though, especially considering the amount of variation within the group. One patient used a cane, one used a conventional joint and corset prosthesis (rather than a PTB), and three subjects were unable to complete all of the trials. There were no dysvascular patients in the group with short limbs and the data provided are estimated based on the pattern observed in traumatic subjects. While the researchers attempted to broaden their sample by being inclusive, they in fact confounded the results by introducing a large number of variables. Finally, the experimental design was satisfactory as it sought to replicate normal walking conditions and there were several trials to include a range of speeds. One flaw, as with Nowrozzi et al. (1983), lies in the physical demands of the trials. Subjects underwent one preliminary trial and six walking trials, each separated by a 30 minute rest. The long testing period may have influenced trials performed later in the day, although there is no way of knowing from the data provided. Finally, the authors did not define how the limbs were measured, only categorizing the limbs in comparison to total body height. This oversight makes the data somewhat difficult to apply, although generalizations can be made.
Gailey et al. (1994) performed a study on energy expenditure using 39 male, traumatic, transtibial amputees. As with Gonzalez et al., the authors found a relationship between limb length and oxygen consumption when subjects were grouped by “short” or “long” residual limb length. Where the previous study failed to define how long and short limbs were classified, Gailey et al. included measurement techniques and defined the limbs in relation to the intact tibia length. They were also careful to clarify that the relationship between limb length and energy expenditure was not apparent until the limbs were separated into the two categories (as opposed to a linear arrangement). The authors posit that small changes may not significantly influence energy expenditure, however surgeons should preserve as much length as possible to minimize impact on energy requirements. Based on the available evidence, the app will collect limb length data from transtibial users in order to categorize them as “short” (<50% of intact length) or “long” (>50% of intact length) for energy consumption and weight calculation purposes.

Only one study was located that investigated the influence of residual limb length on energy expenditure for transfemoral amputees (Bell et al., 2014). In the study, all 26 subjects were military personnel who were at least 24 months post-surgery for traumatic transfemoral amputation. The subjects were categorized based on the ratio of residual limb length to intact limb length; ten had short limbs (20-56%) and 16 had long limbs (57-86%). For the experiment, each subject walked at a comfortable velocity for ten minutes on an indoor track. Bell et al. found that those with long limbs walked 0.17m/s faster than those with short limbs, however no other measurements (O$_2$ consumption/meter, heart rate, etc.) were significantly different between the two groups. As with previous studies, the average comfortable walking speed for both groups was lower compared to normal subjects, and the patients used approximately 60% more oxygen per meter. The outcome was unexpected, as the authors had hypothesized that the altered
anatomy and leverage would produce different results for short versus long limbs. One possible explanation lies in the military surgical technique. The authors suggest that undergoing myodesis may have increased the stability and function of the limbs, regardless of length. Furthermore, the subjects were all members of the military, young (32 yrs. +/-6.1), and presumably male, which may have influenced the outcome due to increased physical fitness. Finally, the authors note that the prosthesis weight was included when calculating oxygen consumption. While most of the amputees used similar equipment, the added weight may have altered the results slightly. This would be especially evident when comparing the amputees’ oxygen consumption to normal subjects, as the amputees’ results would be falsely decreased due to the additional weight. Considering the limitations of the study, the app will not use limb length data to calculate energy consumption for transfemoral patients. It will use limb length for weight related data, using the same definitions as transtibial users.

There are many variables which could impact the caloric needs of an amputee patient. As with the standard formulas, the data provided by the app will only be an approximation of calorie expenditure based on an average amputee. Certain factors influencing energy expenditure are well researched and will be included in the app, while others require further investigation before they can be included.

Age is one variable that can affect energy expenditure of amputees. The previously discussed studies demonstrated the differences between adult and elderly subjects. Older patients tended to walk more slowly, use more oxygen, and have a higher heart rate than younger patients. Pediatric amputees may also exhibit higher energy expenditure when compared with controls. Herbert, Engsberg, Tedford, and Grimston (1994) studied a group of ten transtibial amputees between the age of 6 and 17. The authors found the children walked at the same
comfortable walking speed as their able-bodied peers, unlike adult amputees who walk slower than their peers. In order to maintain the same velocity as the able-bodied children, the amputee subjects used approximately 15% more oxygen. A larger study including children with all levels of lower limb amputation found that only hip disarticulation patients demonstrated a significant increase in energy consumption (Jeans & Karol, 2006). There is a need for more studies on pediatric amputees, especially because the current studies use a broad range of age and etiologies. For the purposes of the mobile app, pediatric amputees will not be included because quantitative data is lacking for that demographic. Furthermore, most fitness apps available on the market do not include children. The app will require the user’s age to calculate resting metabolic rate, however modifications to formulas based on amputation will not be age-dependent due to lack of age specific data in most studies.

Next, etiology has been shown to impact the energy needs of an amputee. Waters et al. (1976) demonstrated this in their study, where dysvascular amputees required more oxygen per meter than traumatic amputees and walked more slowly. Torburn, Powers, Guiterrez, and Perry (1995) found similar results in a study of transtibial amputees. Researchers tested dysvascular and traumatic amputees using five different prosthetic feet. They found that while oxygen consumption per meter was equal between the two groups (attributed to high fitness level), the dysvascular group walked significantly slower than the traumatic patients. The same pattern is found in many studies. Waters and Mulroy (1999) suggest that traumatic patients are generally younger and healthier than dysvascular patients; the increased aerobic capacity and muscle strength allows traumatic amputees to overcome the deficits associated with amputation with less effort. The proposed mobile app will collect etiology data from the user in order to provide a more accurate result. Users will choose between dysvascular and traumatic amputation, as little
data is available regarding energy expenditure for congenital amputees. For the app, the energy requirements of dysvascular transtibial (short) amputees and traumatic knee disarticulation amputees were estimated based on patterns for similar levels. Studies relating energy expenditure and etiology could not be located for hip or partial foot/Symes levels, however these are typically due to cancer and vascular disease, respectively. Therefore, the app will not provide data based on etiology for these levels.

Bilateral amputees present a challenge, not only for prosthetic treatment, but for research as well. Subjects are difficult to find and their varied history and anatomy make experiments difficult to control. Only two articles were located regarding bilateral amputee energy expenditure. Crouse, Lessard, Rhodes, and Lowe (1990) found that a bilateral transfemoral amputee used significantly more oxygen at a comfortable walking speed than able-bodied controls. Only one amputee subject was studied, making the results hard to apply clinically. Huang et al. (1979) studied energy expenditure in four bilateral transfemoral amputees. They determined that the amputees used nearly three times more oxygen per meter than controls. Again, the sample size was small and the results varied significantly between subjects, making it difficult to draw conclusions from the data. The Atlas of Amputations and Limb Deficiencies includes a table detailing energy expenditure for bilateral amputees (Waters & Mulroy, 2004). There is a trend toward higher energy costs for higher levels of amputation, as well as for vascular versus traumatic amputees. The reference provided by the Atlas appears to be incorrect, therefore further analysis of the data quality could not be completed. Due to the small number of studies and subjects, there is not enough information regarding bilateral lower limb amputees to justify their inclusion in the app.
Alignment can influence amputee gait and therefore affects energy expenditure. Schmalz, Blumentritt, and Jarasch (2002) investigated the impact of several alignment changes on oxygen consumption for transtibial and transfemoral patients. For transtibial amputees, they tested sagittal plane misalignments of the foot. The authors found that plantarflexing or dorsiflexing the foot 10° significantly increased oxygen consumption while the velocity was held stable. Anterior and posterior translations of 2cm did not impact energy expenditure while walking. The transfemoral subjects walked at different speeds as researchers shifted the knee joint 1 or 2 cm anterior and posterior to the “normal” alignment. Anterior translation of 2 cm increased oxygen consumption significantly at all velocities tested. Concurrent joint moment measurements revealed an increased hip flexion moment for this alignment. The authors suggest the increase in energy expenditure is largely due to the increased hip extensor activity required to counteract the hip flexion moment. At a “fast” walking speed, there was a significant increase in oxygen consumption with translations of 1 and 2 cm anterior or 2 cm posterior which also correlated with changes in the hip joint moment. Ensuring proper alignment during prosthetic fitting should eliminate the need to consider this variable for the app.

Socket design and componentry choices may also affect the efficiency of gait. A study of transfemoral socket designs showed the Marlo Anatomical Socket (MAS) required less energy to walk than the popular ischial containment design (Traballesi et al., 2011). There is conflicting evidence regarding the energy requirements of a microprocessor knee joint versus a mechanical knee joint. Some studies show a significant decrease in energy cost using a microprocessor device, while others find no difference between the knee joints (Highsmith et al., 2010). For transtibial amputees, foot selection does not seem to impact energy expenditure, although this could vary based on etiology, patient strength, and activity level (Barth, Schumacher, & Thomas,
1992; Torburn et al., 1995). As with alignment, componentry and design choices should be made to provide the most efficient prosthesis possible. For the purposes of the app, it will be assumed that the best option has been selected for an individual user and prosthetic design should have a minimal impact on their energy consumption. If future research proves a repeatable, significant difference between certain components, the app should be updated to reflect those results.

In order to determine the energy requirements of walking for lower limb amputees at each level, the results of the previously discussed studies were evaluated and averaged. The results provided an estimation of the percent increase (PI) in calorie requirements for each amputation level. The methods for determining the PI for each level are detailed below, organized by study. These were then applied to the standard calculation for energy expenditure provided by the American College of Sports Medicine [A] to create a modified equation for use with amputee patients [B].

<table>
<thead>
<tr>
<th>Amputation Level</th>
<th>Percent Increase in Energy (PI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Foot</td>
<td>13.2</td>
</tr>
<tr>
<td>Symes</td>
<td>15.75</td>
</tr>
<tr>
<td>Transtibial (Trauma, Long, &gt;50%)</td>
<td>9.8</td>
</tr>
<tr>
<td>Transtibial (Trauma, Short, &lt;50%)</td>
<td>39.8</td>
</tr>
<tr>
<td>Transtibial (Dysvascular, Long, &gt;50%)</td>
<td>18.8</td>
</tr>
<tr>
<td>Transtibial (Dysvascular, Short, &lt;50%)</td>
<td>48.8*</td>
</tr>
<tr>
<td>Knee Disarticulation (Trauma)</td>
<td>44.5*</td>
</tr>
<tr>
<td>Knee Disarticulation (Dysvascular)</td>
<td>76.5</td>
</tr>
<tr>
<td>Transfemoral (Trauma)</td>
<td>52.25</td>
</tr>
<tr>
<td>Transfemoral (Dysvascular)</td>
<td>89.75</td>
</tr>
<tr>
<td>Hip Disarticulation</td>
<td>80</td>
</tr>
<tr>
<td>Hemipelvectomy</td>
<td>122</td>
</tr>
</tbody>
</table>

*Estimated based on available data
[A] Kilocalories per minute = \( \frac{(\text{MET} \# \text{ value of activity} \times 3.5 \times \text{Weight (kg)})}{200} \)

[B] Kilocalories per minute (kcal\(_{\text{amp}}\)) =
\[
\left( \frac{(\text{MET} \# \text{ value of activity} \times 3.5 \times \text{Weight (kg)})}{200} \right) \times \left[ 1 + \left( \frac{\text{PI}}{100} \right) \right]
\]

* For a table of MET values, see Appendix A

Waters et al. (1976): Two different data sets have been reported from this study for unknown reasons. The widely published data set is lower than the original data set, though the numbers are all within the ranges published in the original paper. The results of both data sets were averaged for: Symes, transtibial (traumatic), transtibial (vascular), transfemoral (traumatic), and transfemoral (vascular).

Pinzur et al. (1992): The data from this study may have been skewed (low) due to the use of dysvascular controls. The velocity and oxygen consumption data for the controls is lower than the normal values used in other studies. The impact of the treadmill use is unknown, though theoretically the influence of the treadmill (whether positive or negative) should be minimized because the patients’ comfortable walking speed was determined during over ground walking. The data comparing the experiment versus controls and the experiment versus healthy adults were averaged for: partial foot (corrected value), Symes, transtibial (vascular), knee disarticulation (vascular), and transfemoral (vascular). The results using control data should account for any influence of the treadmill or experimental design; the results using healthy adult data should negate the impact of the controls’ poor health status.

Gonzalez et al. (1974): The authors provided data as an average for all lengths and also separated by short and long groups. The average increase in energy expenditure for all lengths was 25%, which was averaged with the data from Waters et al. (1976), Pinzur et al. (1992), and Gailey et al. (1994). The long residual limbs required 15% more energy than the average, while
short residual limbs required 15% less. These results were applied to the previously calculated averages for traumatic and dysvascular transtibial users.

Bell et al. (2014): The result for traumatic transfemoral amputees was averaged with that of Waters et al. (1976).

Gailey et al. (1994): The result for traumatic transtibial amputees was averaged with those of Waters et al. (1976) and Gonzalez et al. (1974).

Nowrozzi et al. (1983): The results for hip disarticulation and hemipelvectomy amputees were used.

In order to calculate ideal body weight, adjusted BMI, and basal metabolic rate, the weight of the absent limb segment must be determined. There are several studies which have sought to define segment weight. Many textbooks and articles on the subject of segment length refer to a literature review performed by Osterkamp (1995). Osterkamp determined that data from a study in 1889 were no longer accurate and relevant to the current population. Instead, she averaged data from two other preeminent works by Dempster (1955) and Clauser (1969) since the two studies utilized similar measurement methods and samples. More recently, Durkin and Dowling (2003) have implemented DEXA scanning in order to measure segment weights for a variety of ages, ethnicities, genders, and body types. The researchers used a large sample size and intend to extend the research to a broader range of subjects. This large-scale research should result in a more accurate estimation of body weight proportions once more samples are collected and the data are categorized. For the purposes of the app, Osterkamp’s data (below) will be used on the basis of convention with the acknowledgement that more accurate data may become available in the future.
Dempster and Gaughran (1967) found that all segments of the lower limb had similar densities (1.04-1.07gm/cubic cm). It can be assumed from this finding that the weight of each segment can be divided equally based on the limb length with relative accuracy. For the purposes of the app, the following segment weights will be used based on the level of amputation:

<table>
<thead>
<tr>
<th>Amputation Level</th>
<th>Weight of Absent Limb (% of total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Foot</td>
<td>0.75</td>
</tr>
<tr>
<td>Symes</td>
<td>1.5</td>
</tr>
<tr>
<td>Transtibial (Long, &gt;50%)</td>
<td>2.6</td>
</tr>
<tr>
<td>Transtibial (Short, &lt;50%)</td>
<td>4.8</td>
</tr>
<tr>
<td>Knee Disarticulation</td>
<td>5.9</td>
</tr>
<tr>
<td>Transfemoral (Long, &gt;50%)</td>
<td>8.2</td>
</tr>
<tr>
<td>Transfemoral (Short, &lt;50%)</td>
<td>13.7</td>
</tr>
<tr>
<td>Hip Disarticulation</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Ideal body weight (IBW) is a commonly used metric in dietetics and exercise science. Dieticians use this number to estimate calorie requirements for their patients; IBW can also be used when creating physical training programs for weight loss or maintenance. For amputees, IBW can be difficult to apply due to altered anatomy. Using the standard formula [C], amputees may find that the result overestimates their IBW because the amputated limb is not taken into account (Piland & Adams, 2009). For example, it is common to calculate the difference between current weight and ideal weight when setting weight control goals. The difference between using the standard IBW calculation versus the corrected formula [D] can be greater than 15% for a
female transtibial patient. The app will allow users to calculate their IBW by correcting for the weight of the absent segment.

\[
\text{Male: } \text{IBW} = \left(\text{Height (in)} - 60\right) \times 6 + 106 \\
\text{Female: } \text{IBW} = \left(\text{Height (in)} - 60\right) \times 5 + 100
\]

\[
\text{Male: } \text{IBW}_c = \text{IBW} - \left(\text{IBW} \times \text{Segment Weight }\%ight) \\
\text{Female: } \text{IBW}_c = \text{IBW} - \left(\text{IBW}\times\text{Segment Weight }\%ight)
\]

Body mass index (BMI) is another valuable measurement tool used by individuals, physicians, dieticians, and trainers to assess body condition. A BMI score is calculated by dividing the patient weight by the height\(^2\) to find the density [E]. The score is then compared with a standardized chart indicating body condition, ranging from underweight to obese. While many argue that body mass index is irrelevant because it does not distinguish between muscle mass and fat, it remains a staple in many texts and practices and can be useful as a general indicator of health (Charney & Malone, 2008; American College of Sports Medicine, 2009; Pitetti & Pedrotty, 2009). A retrospective study by Flegal, Graubard, Williamson, and Gail (2007) found a correlation between BMI and risk of death due to cardiovascular disease, obesity-related cancers, and diabetes with concurrent kidney disease. Obese subjects were associated with increased mortality due to all three conditions, while overweight subjects demonstrated increased mortality risk from diabetes with kidney disease. Obesity was also correlated with higher mortality overall compared with other body conditions.

For amputees, the standard calculation for BMI may not be accurate since it does not account for the reduction in weight from the absent limb. Tzamaloukas, Patron, and Malhotra (1994) argued that BMI scores for amputees are falsely decreased because the weight of the limb is not included in the calculation. They presented a corrected BMI calculation and validated it by
comparing the scores with the results of nutritional assessments. The equation uses the postamputation weight and adjusts the height component according to the amount of weight lost by amputation. The corrected BMI scores more accurately categorized patients, especially for those who fell into extremes or had bilateral amputations. In a letter to the editors of the Journal of the American Dietetic Association, Himes (1995) also suggested that BMI scores for amputees must be adjusted to accommodate their unique circumstances. He recommended correcting the postamputation weight by including the weight of the absent limb segment \[F\]. In the *ADA Pocket Guide to Nutrition Assessment*, the authors present a method for determining the corrected ideal body weight for amputees but do not explicitly suggest a corrected BMI calculation (2008). The equations created by Himes (1995) and Tzamaloukas et al. (1994) were compared using Microsoft Excel and yielded identical results for 30 sample patients. For the mobile application, the equation from Himes will be used because preamputation weight (required for the equation from Tzamaloukas et al.) is not always available.

\[E\] \[\text{BMI} = \frac{\text{Weight (kg)}}{\text{Height}^2 (m^2)}\]

\[F\] \[\text{BMI}_c = \frac{[\text{Weight (kg)} / (1 - \text{Segment Weight ()})]}{\text{Height}^2 (m^2)}\]

Resting metabolic rate (RMR) is often calculated to give care providers and patients an approximation of the amount of energy (kilocalories) required per day to maintain homeostasis, body functions, and normal daily activities. The *Pocket Resource for Nutrition Assessment* does not provide a recommendation regarding the use of actual body weight versus corrected body weight when calculating RMR for amputees (Piland & Adams, 2009). It is possible that amputation is irrelevant when calculating RMR because the loss of muscle mass (requiring calories) negates the missing weight of the absent limb segment. Previously discussed studies typically found no difference in resting oxygen consumption (mL/kg/min) between amputees and
controls, which would suggest that resting metabolic rates are similar between the groups (Nowrozzi et al., 1983; Pinzur et al., 1992; Gailey et al., 1994). The app will use the standard RMR calculation to provide users with an estimation of their daily caloric needs based on sex, height, weight, and age [G].

\[
\text{Male: } \text{RMR} = 66.47 + (13.75 \times \text{Weight (kg)}) + (5.0 \times \text{Height (cm)}) - (6.76 \times \text{Age}) \\
\text{Female: } \text{RMR} = 655.1 + (9.56 \times \text{Weight (kg)}) + (1.85 \times \text{Height (cm)}) - (4.68 \times \text{Age})
\]

**Discussion**

Amputees are at risk for obesity and correlated health problems and current recommendations point to diet and exercise as the primary means to maintain or lose weight. There is a need for a user-friendly tool that will allow them to track their physical activity and progress because current mobile apps do not account for the unique energy requirements of amputees. In order to further demonstrate the impact of amputation on calorie balance and body condition scoring, the formulas presented above can be applied to a sample patient. Ms. Smith is a 30 year old female who has a long transfemoral limb due to a traumatic amputation. Her current height and weight are 5’4” and 145 lbs, respectively. She walks for 30 minutes a day at a moderate pace (2.8-3.2 mph).

\[\text{Kilocalories per minute} = (3.5 \times 3.5 \times 145) / 200 = 8.88 \text{ (266.4 kcal for 30 min)}\]

\[\text{Kilocalories per minute (kcal}_{\text{amp}}) = [(3.5 \times 3.5 \times 145) / 200] \times [1 + (52.25 / 100)] = 13.52 \text{ (405.6 kcal for 30 min)}\]

\[\text{IBW} = [(64 - 60) \times 5] + 100 = 120 \text{ lbs} \Rightarrow \text{actual wt/IBW} = 120\% = \text{overweight}\]

\[\text{IBW}_{c} = 120 - (120 \times 0.082) = 110.2 \text{ lbs} \Rightarrow \text{actual wt/IBW}_{c} = 131\% = \text{obese}\]

\[\text{BMI} = 65.9 / 1.63^2 = 24.8 \text{ (normal)}\]

\[\text{BMI}_{c} = [65.9 / (1-0.082)] / 1.63^2 = 27 \text{ (overweight)}\]
This sample illustrates that standard formulas may underestimate body condition and caloric requirements of amputees. The sample patient was categorized as normal using BMI, but overweight using BMIc. For 30 minutes of walking, the corrected formula shows an increased calorie expenditure of 139.2 kcal or 52%. The proposed mobile app will use the modified formulas [B, D, F] and resting metabolic rate [G] to provide users with a more accurate estimation of calorie balance.

Further research will be necessary to broaden the scope of the proposed app and allow for creation of a functional and accurate program. Most importantly, researchers must explore the impact of amputation level and cause on energy expenditure in a consistent way. Once a standard testing protocol is determined, researchers can expand into activities beyond walking, such as running or cycling. There is need for a specialized method of calorie and activity tracking for amputees, and this demand should drive future researchers as they strive to improve the quality and quantity of life for amputees.

Resources


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**Appendix A: Chart for METS**

<table>
<thead>
<tr>
<th>2.0</th>
<th>walking, household</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>walking, less than 2.0 mph, level, strolling, very slow</td>
</tr>
<tr>
<td>2.8</td>
<td>walking, 2.0 mph, level, slow pace, firm surface</td>
</tr>
</tbody>
</table>
Resource: