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Prevalence of heat and perspiration discomfort inside prostheses: Literature review

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Abstract—People with limb amputation deal with thermal stresses in their daily activities. Unfortunately, in the majority of this population, all thermal transfer mechanisms, including convection, radiation, evaporation, and conduction, can be disturbed due to the prosthetic socket barrier, decreased body surface area, and/or vascular disease. The thermal environment inside prosthetic sockets, in addition to decreased quality of life and prosthesis use, comfort, and satisfaction, could put people with amputation at high risk for skin irritations. The current review explores the importance of thermal and perspiration discomfort inside prosthetic sockets by providing an insight into the prevalence of the problem. The literature search was performed in two databases, PubMed and Web of Knowledge, to find relevant articles. After considering the review criteria and hand-searching the reference sections of the selected studies, 38 studies were listed for review and data extraction. This review revealed that more than 53% of people with amputation in the selected studies experienced heat and/or perspiration discomfort inside their prostheses. In spite of great technological advances, current prostheses are unable to resolve this problem. Therefore, more attention must be paid by researchers, clinicians, and manufacturers of prosthetic components to thermal-related biomechanics of soft tissues, proper fabrication technique, material selection, and introduction of efficient thermoregulatory systems.

Key words: amputation, amputee, comfort, heat, perspiration, prosthesis, residual limb, skin, socket, temperature.

INTRODUCTION

Global prevalence estimates of amputation are difficult to obtain due to incomplete international disability databases and limited resources to record national levels of disabilities [1]. The United States had nearly 1.6 million people with amputation based on 2005 reports [2]. In the United States, it could be estimated that the population with amputation will increase to 3.6 million by 2050 [2]. It could be estimated that nearly 30 million people in Africa, Asia, and Latin America require prostheses, orthoses, and other assistive devices [1]. Annually in the United Kingdom, there are nearly 5,000 new referrals to prosthetic service centers [3]. These statistics could represent high demand for prostheses in the near future.

The socket is the main component of a prosthesis that primarily provides structural coupling, control, and proper transfer of forces at its interface with the residual limb [4]. Socket comfort directly affects function and extent of prosthesis use in people with amputation [5]. Good prosthesis fit and suspension requires a snug total contact fit that consequently limits ventilation and air circulation at the socket-skin interface. Inappropriate socket ventilation and low moisture permeability of socket walls leads to higher residual-limb skin temperature and perspiration accumulation inside the socket. These consequences could negatively affect quality of life, prosthesis

Abbreviations: Botox = Botulinum toxin, CI = confidence interval, MeSH = medical subject heading.

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suspension, prosthesis use, and activity level. Moreover, they cause discomfort, skin irritation, skin maceration, friction blisters, infection, unpleasant odor, and an environment for bacterial invasion to hair follicles of the residual limb [6–17]. Findings of a survey in 2001 revealed that thermal discomfort with the prosthetic socket could decrease quality of life in many people with amputation [12]. In another study, 60 to 70 percent of people with amputation reported high perspiration inside their prosthetic socket as a major problem [18].

Skin care of the residual limb is of great importance in that any skin irritation could endanger load bearing and prosthesis use in spite of appropriate socket fit [15,19–20]. Skin problems that could easily be seen in people with amputation include those with mechanical sources (epidermoid, cysts, calluses, verrucous hyperplasia), allergic reactions (inflammation, eczema, contact dermatitis, rash), and fungal or bacterial infections [14,21]. In the population with amputation, the presence of at least one skin problem is estimated to be between 32 and 73.9 percent [22–24]. Skin temperature increase is a sign of tissue stress and its presence with slight moisture could cause friction blisters [25–27]. Naylor showed that skin with slight moisture is more susceptible to blisters than wet or dry skin [28]. This same skin condition occurs inside the prosthetic socket. Legro et al., in their survey to determine important issues about prosthesis use by people with amputation, revealed that prevention of skin blisters is one of the three most important issues [16].

Findings of a study by Peery et al. revealed that a 1°C to 2°C increase in residual-limb skin temperature inside the prosthetic socket could cause discomfort [29]. Thermal comfort is a general sense of the body that would be disturbed in the presence of limb temperature imbalance. It means that if one part of the body is hot and another is cold, the person feels thermal discomfort [30]. According to the standards of the American Society of Heating, Refrigerating, and Air Conditioning Engineers, thermal comfort is a satisfactory condition from the environment temperature [30–31]. Limited attention has been paid to the study of thermal discomfort inside the prosthetic socket [32]. The majority of temperature recordings of the residual limb are performed to detect the level of reamputation surgery, vascular integrity, and exploration of phantom pain syndrome [33]. A general insight regarding the prevalence and importance of heat and/or perspiration discomfort with prostheses could draw more attention to resolving this long-lasting problem. The current study was designed to review the literature and explore the prevalence of heat and/or perspiration discomfort by providing a general insight for researchers, clinicians, and prosthetic component manufacturers to resolve the problem.

METHODS

An electronic literature search was performed in two databases, PubMed and Web of Knowledge (now called Web of Science), to find relevant articles. The selection of two databases was based on the guidelines of the American Academy of Orthotists and Prosthetists and an evidence report that determined their appropriate coverage for the most relevant journals in the field of orthotics and prosthetics [34]. The chosen time period was the first date possible for each database until November 2013. The search strategy was based on the Patient, Intervention, Comparison, and Outcome system, using the following key words combined as a search string:

1. “Residual limb” OR stump* OR “amputation stumps” [medical subject heading (MeSH)]
2. Amputee* [MeSH] OR amputation [MeSH]
3. Search 1 OR 2
4. Socket*
5. Prosthesis OR prostheses OR “artificial limbs” [MeSH] OR (artificial AND limb)
6. Search 4 OR 5
7. Comfort* OR discomfort*
8. Hyperhidrosis [MeSH] OR hyperhydrosis OR sweat [MeSH] OR sweating [MeSH] OR perspiration*
9. Hydration*
10. “Skin temperature” [MeSH] OR (skin AND temperature)
11. Heat*
12. Thermal
13. Search 7 OR 8 OR 9 OR 10 OR 11 OR 12
14. Search 3 AND 6 AND 13

The results of both databases were entered into EndNote reference management software (Thomson Reuters; Philadelphia, Pennsylvania), and all duplicate results were removed. Then, two independent reviewers assessed the title and abstract of all identified studies for adaptation to the inclusion criteria. The reviewers included published journal articles written in English that directly or indirectly reported heat and/or perspiration discomfort with prostheses and with subject participants with amputation.

Moreover, review articles, case reports, case studies, and technical notes were excluded. Although none of the review articles reported the heat and/or perspiration prevalence, the reference sections of these articles were searched to find any potential studies that were not found in the electronic search.

Following abstract-based assessment, the full text of all selected studies was reviewed to check their adaptability with review criteria. Additionally, the reference sections of the selected full-text articles were examined to find other potential studies to extend the included articles. The reviewers independently extracted demographic, methodological, and results data from the selected studies. For methodological data extraction, the design, assessment method, main outcome measure, and total number or percentage of the study population with heat and/or perspiration discomfort were defined. Finally, the results of both reviewers were compared and all differences were resolved through discussion.

To determine the prevalence of people with amputation and heat and/or perspiration discomfort in the selected studies, the weighted summary proportions with a 95 percent confidence interval (CI) were calculated using MedCalc statistical software version 13.0.0 (MedCalc Software; Ostend, Belgium).

RESULTS

A preliminary literature search in two databases without consideration of review criteria identified 330 abstracts. Application of review criteria caused the removal of 283 abstracts. Two reviewers assessed the full text of 47 remaining studies, i.e., 14 percent of the preliminary results. Following a full-text review, 13 full-text articles were removed from the list due to nonfulfillment of one or more review criteria. In addition, two more studies were removed from the list because their full texts were not accessible [35–36]. With the addition of 6 studies after reference section examination of the selected full texts, 38 studies in total were identified for data extraction. **Figure 1** shows the procedure for study selection.

Table 1 represents the demographic characteristics of subjects in the selected studies [6–7,11–13,16–18,21,29,37–64]. The number of subjects in the studies ranged from 4 [43,48] to 581 [59]. Unfortunately, the demographic characteristics of participants were heterogeneous and difficult to compare. Based on those studies

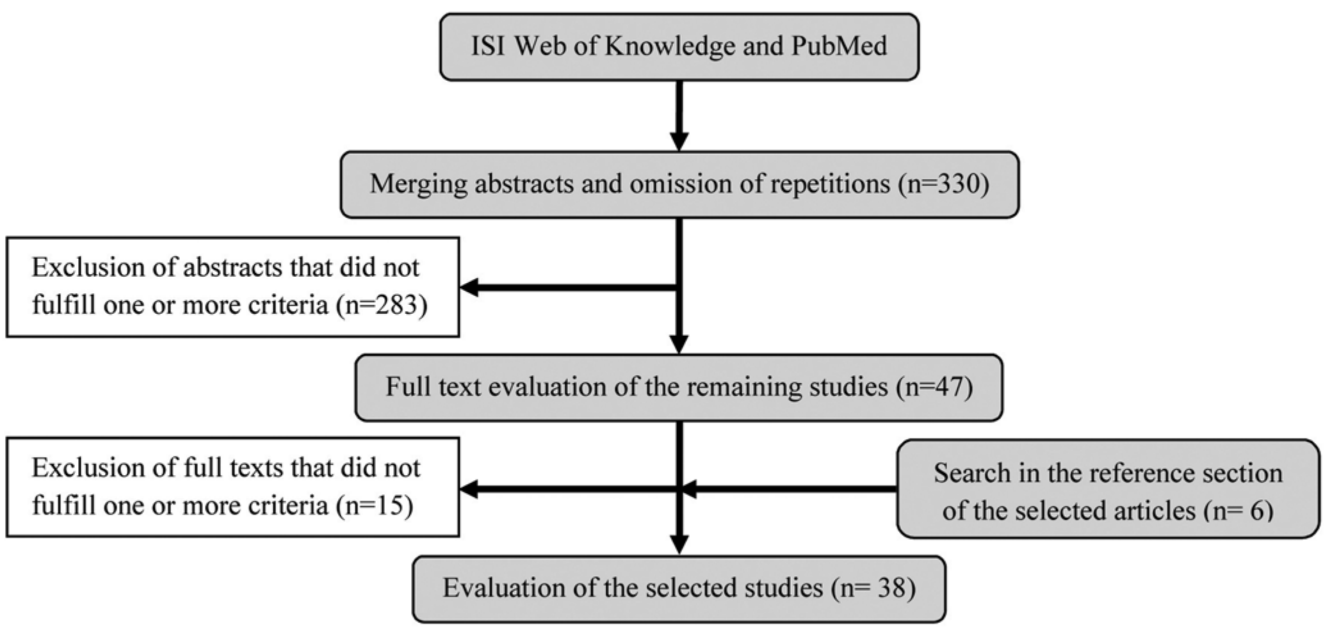

Figure 1.
Procedure for selection of studies from two databases.

Table 1.
Demographic characteristics of participants in selected studies.

Study	Participants (*n*)	Age (yr), mean ± SD (range)	Amputation	Time Since Amputation (yr), mean ± SD (range)	Daily Prosthesis Use (h), mean ± SD (range)
Köhler et al., 1989 [6]	15	42.26 ± 14.62 (17–67)	UL, LL	NR	NR
Kejlaa, 1993 [37]	48	46.3 (4–83)	UL	23.3 (0–51)	>8
Burger & Marincek, 1994 [38]	243	NR	UL	28.6 ± 1	11
Cluitmans et al., 1994 [39]	26	NR	LL	11.05	NR
Datta et al., 1996 [13]	54	48.35 (22–80)	LL	0.40 (0.03–2)	10.42
Pereira et al., 1996 [40]	30	(15–50)	UL	NR	>9
Susak et al., 1996 [41]	16	43.5 ± 7.1 (27–52)	LL	1.2 ± 5.2 (3–12)	NR
Boonstra et al., 1996 [42]	8	41 (24–62)	LL	16 (2–50)	NR
Leow et al., 1997 [43]	4	NR	UL	≥2	(8–10)
Dasgupta et al., 1997 [44]	27	49.87 ± 13.57 (21–76)	LL	16.68 ± 15.09 (1–52)	14.45 ± 2.5 (8–18)
Lake & Supan, 1997 [18]	56	52.9 (15–85)	LL	6.5	NR
Hachisuka et al., 1998 [45]	32	44.5 ± 16	LL	0.90 ± 1.15	NR
Legro et al., 1999 [16]	92	55 (22–81)	LL	(1–53)	NR
Vannah et al., 1999 [46]	258	(2–21)	LL	NR	>8
Otter et al., 1999 [47]	20	49.05 (25–74)	LL	8.35 ± 7.25	NR
Heim et al., 2000 [48]	4	70 (50–79)	LL	NR	NR
Hatfield & Morrison, 2001 [49]	56	51.45 ± 17.9 (11–78)	LL	16.3 (1–69)	NR
Hachisuka et al., 2001 [17]	83	53.4 ± 14.4	LL	14.8 ± 15.2	>7
Hagberg & Brånemark, 2001 [12]	90	48 (20–69)	LL	22 (2–52)	>10
Dillingham et al., 2001 [50]	78	40.4 ± 13.4	LL	7.5 ± 2.8	11.5 ± 4.7
Davidson, 2002 [51]	70	NR	UL	NR	1.75 ± 1.45
Coleman et al., 2004 [52]	13	49.4 ± 9.6 (31.5–65.8)	LL	24.4 ± 11 (4.7–39.3)	10.3
Peery et al., 2005 [29]	5	44 ± 14	LL	≥2	8
Van de Weg & Van der Windt, 2005 [53]	220	62.1 ± 17.5	LL	16.7 ± 16.2	>6
Meatherall et al., 2005 [54]	41	(40–88)	LL	≥0.5	11.25 ± 5.25
Biddiss & Chau, 2007 [55]	242	26.25 ± 10.5 (1–80)	UL	(0.4–6.6)	4.37 ± 2.12
Charrow et al., 2008 [56]	8	28.5 (20–42)	UL, LL	0.68 (0.33–1.16)	NR
Almassi et al., 2010 [57]	335	43.04 ± 6.32	LL	NR	NR
Berke et al., 2010 [58]	481	45	UL, LL, ML	≥1	NR
Reiber et al., 2010 [59]	581	45 ± 4.4	UL, LL, ML	20.85 ± 2.6	NR
Kern et al., 2011 [11]	9	49.7	LL	(1–27)	NR
Meulenbelt et al., 2011 [21]	44	58 ± 17	LL	19 ± 18	>6
Visscher et al., 2011 [7]	13	>18	LL	14.5 ± 12 (3–47)	12.2 ± 2.7
Ali et al., 2012 [60]	243	44.02 ± 6.26	LL	22.01 ± 5.95	11.67 ± 3.25
Østlie et al., 2012 [61]	224	53.7	UL	24	NR
Yang et al., 2012 [62]	247	62 ± 3	UL, LL	38 ± 3	NR
Ali et al., 2012 [63]	9	49.3 ± 15.0	LL	≥3.5	NR
Gholizadeh et al., 2013 [64]	90	47.77 ± 7.0	LL	23.80 ± 4.2	11.80 ± 3.34

LL = lower limb, ML = multiple limbs, NR = not reported, SD = standard deviation, UL = upper limb.

that reported the mean participant age, time since amputation surgery, and daily prosthesis use, these values were 48.12 ± 8.78 yr, 15.73 ± 9.71 yr, and 9.89 ± 3.55 h, respectively (**Table 1**). The lower limbs were evaluated more than upper limbs in the selected studies. Moreover, three studies evaluated both upper and lower limbs; in two additional studies, the evaluation was based on upper, lower, and multiple limbs.

Table 2 represents methodological evaluations of the selected studies [6–7,11–13,16–18,21,29,37–64]. Studies that reported heat and/or perspiration discomfort the most were conducted in 1996, 2001, and 2012, each with four studies. As can be seen from **Table 2**, the heat and/or perspiration discomfort inside prostheses is a long-lasting issue. With respect to study design, 27 were descriptive observations, 9 were prospective experiments, and 2 were retrospective observations. Survey and medical

Table 2.
Methodological characteristics of selected studies.

Study	Design	Assessment Method	Main Outcome Measure	Heat/Perspiration Complaint, *n* (%)
Köhler et al., 1989 [6]	PECBAT	Clinical examination	Objective evaluation of residual-limb bacteria and effect of antiseptics.	NR
Kejlaa, 1993 [37]	DOCS	Medical records, survey	Subjective evaluation of concerns and prosthesis-related problems in persons with amputation.	38 (79)
Burger & Marincek, 1994 [38]	DOCS	Medical records, survey	Subjective evaluation of upper-limb prosthesis use/nonuse.	111 (45.7)
Cluitmans et al., 1994 [39]	ROCC	Medical records, survey, clinical examination	Subjective evaluation and comparison of three transtibial prosthetic socket designs.	11 (42)
Datta et al., 1996 [13]	DOCS	Survey	Subjective evaluation and comparison of two transtibial prosthetic socket designs.	>20 (41)
Pereira et al., 1996 [40]	DOCS	Survey	Subjective evaluation of prosthesis use and prosthesis-related benefits and problems.	10 (33)
Susak et al., 1996 [41]	PECBAT	Survey, clinical examination	Subjective evaluation and clinical examination of Methenamine effect on sweating rate.	6 (100)
Boonstra et al., 1996 [42]	PERCOT	Survey	Subjective evaluation and comparison of two transtibial prosthetic suspension systems.	5 (62.5)
Leow et al., 1997 [43]	DOCS	Observation	Professional report of prosthesis discoloration due to fungal colonization.	4 (100)
Dasgupta et al., 1997 [44]	PECBAT	Medical records, survey, clinical examination, objective tests	Subjective and objective evaluation of transtibial suspension system.	NR
Lake & Supan, 1997 [18]	DOCSEC	Survey	Subjective evaluation of skin dermatological problems when using lower-limb prosthetic suspension system.	31 (55.3)
Hachisuka et al., 1998 [45]	DOCS	Survey	Subjective evaluation of transtibial socket design.	>6 (20)
Legro et al., 1999 [16]	DOCSEC	Survey	Subjective evaluation of prosthesis-related issues of importance.	NR
Vannah et al., 1999 [46]	DOCSEC	Survey	Subjective evaluation of function and prosthesis-related problems.	51 (20)
Otter et al., 1999 [47]	PECOT	Medical records, survey, clinical examination	Subjective evaluation and clinical examination of skin-related problems in comparison with two knee prosthetic socket designs.	8 (40)
Heim et al., 2000 [48]	DOCS	Medical records, observation	Professional report of prosthesis effect on persons with tumor and amputation.	NR
Hatfield & Morrison, 2001 [49]	ROCC	Medical records, survey	Subjective evaluation of advantages and/or disadvantages of cushion and pin-lock liners in persons with amputation.	NR
Hachisuka et al., 2001 [17]	DOCS	Survey	Subjective evaluation of hygiene-related problems with transtibial socket design.	39 (47)
Hagberg & Brånemark, 2001 [12]	DOCS	Survey	Subjective evaluation of prosthesis use, quality of life, and prosthesis-related problems.	65 (72)
Dillingham et al., 2001 [50]	DOCSEC	Medical records, survey	Subjective evaluation of prosthesis use and satisfaction.	18 (23.1)
Davidson, 2002 [51]	DOCSEC	Survey	Subjective evaluation of prosthesis use, satisfaction, and life style.	38 (55)
Coleman et al., 2004 [52]	PERCOT	Clinical examination, survey	Subjective evaluation and clinical examination to compare two transtibial suspension systems.	8 (61)

Table 2. (cont)
Methodological characteristics of selected studies.

Study	Design	Assessment Method	Main Outcome Measure	Heat/Perspiration Complaint, *n* (%)
Peery et al., 2005 [29]	DOCS	Clinical examination	Clinical examination of residual-limb skin temperature inside prosthesis.	NR
Van de Weg & Van der Windt, 2005 [53]	DOCSEC	Survey	Subjective evaluation of satisfaction and problems with three transtibial socket interfaces.	53 (26.4)
Meatherall et al., 2005 [54]	DOCSEC	Medical records, survey	Subjective evaluation of disability and quality of life in diabetic persons with lower-limb amputation.	26 (63)
Biddiss & Chau, 2007 [55]	DOCSEC	Survey	Subjective evaluation of abandonment factors of upper-limb prostheses.	200 (82.5)
Charrow et al., 2008 [56]	PECBAT	Survey	Subjective evaluation of sweating, pain, prosthetic fit, and function before and after Botox injection.	8 (100)
Almassi et al., 2010 [57]	DOCSEC	Medical records, clinical examination, survey	Subjective evaluation and clinical examination of factors contributing to skin disorders.	223 (66.5)
Berke et al., 2010 [58]	DOCSEC	Survey	Subjective evaluation of satisfaction with prosthetic care.	317 (66)
Reiber et al., 2010 [59]	DOCSEC	Survey	Subjective evaluation of characteristics, health status, quality of life, prosthetic use, and satisfaction of participants with amputation.	129 (22.2)
Kern et al., 2011 [11]	PECBAT	Survey, observation, clinical examination	Subjective evaluation and clinical examination of sweating rate before and after Botox injection.	9 (100)
Meulenbelt et al., 2011 [21]	DOCSEC	Survey, clinical examination	Subjective evaluation and clinical examination of skin problems in participants with amputation.	11 (25)
Visscher et al., 2011 [7]	PERCOT	Observation, clinical examination	Objective evaluation and clinical examination of residual-limb skin hydration and condition with transtibial socket design.	NR
Ali et al., 2012 [60]	DOCSEC	Survey	Subjective evaluation of satisfaction and prosthesis-related problems.	NR
Østlie et al., 2012 [61]	DOCSEC	Medical records, survey	Subjective evaluation of prosthesis rejection rate and its contributing factors.	NR
Yang et al., 2012 [62]	DOCSEC	Medical records, survey	Subjective evaluation of residual-limb skin problems.	12 (17.9)
Ali et al., 2012 [63]	DOCOT	Objective tests, survey	Clinical examination of prosthesis-skin interface pressure and subjective evaluation of satisfaction.	NR
Gholizadeh et al., 2013 [64]	DOCSEC	Survey	Subjective evaluation and comparison of two transfemoral suspension systems.	NR

Botox = Botulinum toxin, DOCS = descriptive observational case series, DOCOT = descriptive observational cross-over trial, DOCSEC = descriptive observational cross-sectional, NR = not reported, PECBAT = prospective experimental controlled before-and-after trial, PECOT = prospective experimental cross-over trial, PERCOT = prospective experimental randomized cross-over trial, ROCC = retrospective observational case-controlled.

records were the most used assessment methods in the selected studies, followed by clinical examination. Subjective evaluation of people with amputation and prosthesis-related issues by standard or author-designed questionnaires was the main outcome measure for the majority of the selected studies.

In the current review of the literature, the number and percentage of the population experiencing heat and/or perspiration were extracted based on participants' response to thermal-related trials and questions in surveys. Of the 38 selected studies for this review, 27 reported the total number of participants with heat and/or perspiration discomfort (**Table 2**). Subjects from these studies were pooled (total: 3,126) to calculate the weighted summary proportion of those with heat and/or perspiration discomfort (**Figure 2**). The results revealed that these studies had a significant heterogeneity (Cochran Q = 749.97, $p < 0.001$) and inconsistency (I^2 = 96.53); therefore, the true proportion estimate significantly varied between different studies. Due to inconsistency between the true estimates of the reviewed studies, we used the random effects model to calculate weighted summary proportion. In the random effects model, the summary proportion is calculated based on the weighted average of proportions reported in the studies [65]. According to the calculations, at least 53.68 percent (with a 95% CI of 43.63–63.58) of people with amputation have complaints regarding heat and/or perspiration inside prostheses. **Figure 2** shows the heat and/or perspiration discomfort proportion and 95 percent CI for each individual study (n = 27) and the weighted summary proportion presented in the forest plot.

DISCUSSION

In spite of the great importance of thermal discomfort inside prostheses and its subsequent effects on skin integrity,

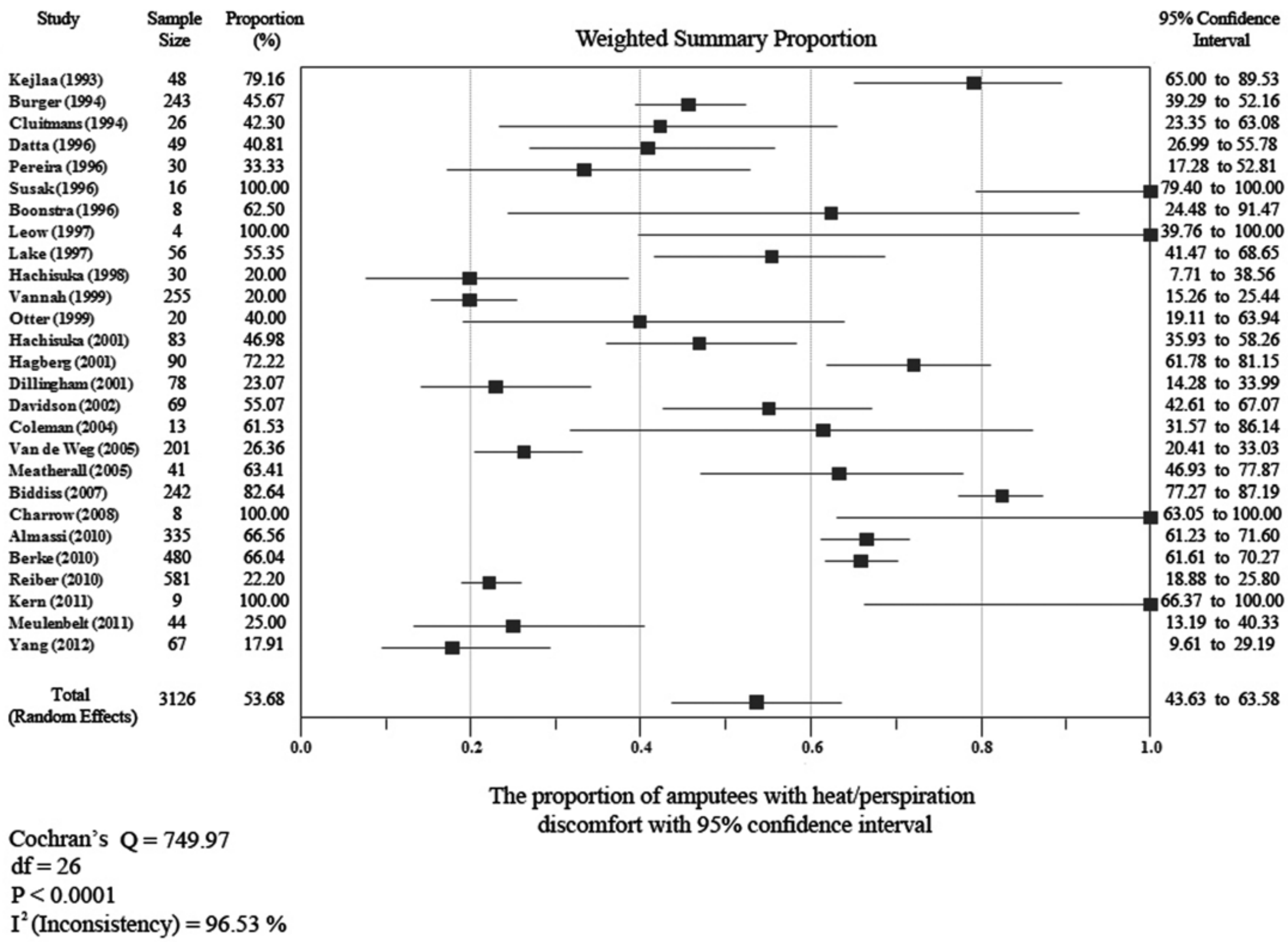

Figure 2.
Forest plot and weighted summary proportions of selected studies that reported number of participants with heat and/or perspiration discomfort.

quality of life, satisfaction, and prosthesis use, limited attention has been paid to directly resolve this problem by researchers, clinicians, and prosthetic component manufacturers. As a point of view, this could be attributed to the lack of a consensus regarding the prevalence of the problem in the population with amputation. The current study, although a narrative literature review based on the knowledge of the authors, is the first evidence aimed at providing a general insight regarding the high prevalence of thermal problems inside prostheses. This review, based on the available reports of heat and/or perspiration discomfort in the selected studies, identified that at least 53.68 percent of the studied people with amputation complain about thermal-related discomfort inside their prostheses regardless of their prosthesis type and level of amputation.

In the vast majority of people with amputation, all thermal transfer mechanisms, including convection, radiation, evaporation, and conduction, can be disturbed due to the socket barrier, decreased body surface area, and/or vascular disease [8–9,66]. This review identified that the unpleasant thermal environment inside the prosthetic socket is a long-lasting problem complained about by many people with amputation in the literature. Vultee (1958) [15] and Foort (1965) [67], in two preliminary reports of the problem, pointed out that skin maceration of the residual limb can be a result of high perspiration and thermal environment inside the prosthetic socket. Foort correlated this unpleasant environment with the existence of leather-rubber liners, high thickness of prosthesis walls, enclosed distal socket, and snug socket fit [67]. Technological advances in the field of prosthetics followed by the introduction of new prosthesis and residual-limb interface materials could not resolve the problem. The elastomeric liner materials of total surface-bearing sockets adapt to the shape of the residual limb because of their specific viscoelastic property to provide a snug fit for improved weight bearing and suspension. Despite this advantage, these liners prevent ventilation and air circulation at the prosthesis and residual-limb interface [68]. Moreover, low moisture permeability of the liner materials and direct contact of the skin with plastic, silicone, and other inorganic materials prevents sweat evaporation, which causes immersion of the residual limb in a salty liquid pool inside the prosthetic socket that consequently leads to skin irritations [7–8,15,69]. The thickness of materials applicable in the construction of prosthetic sockets and liners could influence their thermal conductivity. Klute et al., using a specially designed instrument, measured the thermal conductivity of prosthetic sockets and liners to find the relationship between material temperature transfer ability and residual-limb skin temperature [9]. According to their findings, changing the construction material of prosthetic liners or their thickness would significantly affect the skin temperature of the residual limb [9].

Activity is another factor that could significantly exacerbate the thermal environment inside the prosthetic socket. A small number of studies were found in the literature investigating thermal skin fluctuations of the residual limb during activity. This difficult investigation requires positioning thermistors in the socket-skin interface, which consequently could give the person with amputation discomfort, skin irritation, and ulceration [10]. Peery et al., in a similar investigation, measured the skin temperature of the residual limb in people with transtibial amputation during two positions of rest and walking [29]. They found that wearing the prosthesis at rest and after 10 min of walking would increase skin temperature by 0.8°C and 1.7°C, respectively [29]. The amount of skin temperature increase was 1.5°C following walking in the study by Klute et al. [9]. Huff et al. claimed that people with amputation might need more than 1 h of rest following activity to return to the basal skin temperature [10].

Mapping the temperature distribution of the residual limb is a significant step toward selection of appropriate methods for counteracting the prosthetic socket thermal environment. This investigation could be conducted both experimentally by attaching thermistors to the skin of the residual limb and virtually by simulation software. Peery et al., using three-dimensional finite element analysis, found that in transtibial residual limbs, due to the position of the muscles, the lowest temperature and the coldest region are located at the anterior and distal regions, respectively [70]. To reach this conclusion, they focused on metabolism and blood perfusion of the muscles as two sources of temperature production [70]. Although the thermographic map by Peery et al. seems to be true for most people with transtibial amputation, some factors such as age, lifestyle, and physical condition, by affecting metabolism and perfusion, could contribute to different temperature distribution patterns [70]. In addition, thermal characteristics of tissues depend on their location in the body and may vary among different people.

In spite of previous efforts and current trends to resolve the heat and perspiration discomfort with prostheses, no generally accepted solution has been found. In 2009, Klute et al. gathered and suggested some solutions to the problem in people with lower-limb amputation [4]. These were use of breathable materials for construction of prosthetic sockets and liners; perforation of socket walls by cutting some openings; use of antiperspirant medications, powders, and sprays to physiologically decrease skin perspiration; use of psychological methods to reduce thermal discomfort; and design and manufacture of prosthetic-specific cooling systems [4]. Although recently the use of breathable nanomaterials with high thermal conductivity in the structure of prosthetic sockets and liners has been proposed [71–72], there are some doubts about their safety and the manner in which these materials behave over the body surface [73–74]. Perforation of prosthetic socket walls or fabrication of prostheses by perforated materials has weak efficiency, causes sound, and decreases prosthesis durability and suspension [67,75]. Furthermore, the socket wall perforations could result in formation of shear stress over the residual limb that consequently could result in soft tissue breakdown. Antiperspirant medications, local ointments, powders, and sprays could decrease perspiration by functional limitation of sweat glands. These materials have an unpleasant odor and are associated with risk of allergic reactions and systemic disturbances [15,41,76]. Although Botulinium toxin (Botox) injection could successfully decrease perspiration, it is considered an unacceptable solution. Botox injection is an invasive treatment that could cause pain, hematoma at the injection site, mouth and olfactory tract dryness, and optical problems. Moreover, it requires periodic injections to maintain effectiveness [11]. In some cases, hypnosis, psychotherapy, and biofeedback could be implemented to decrease sweating [77]. These methods have limited generalizability and usually are long-term solutions [77–78]. Many commercially available cooling systems are designed to decrease body temperature in athletes, soldiers, firefighters, and other professionals who need supportive clothes during long activities [79]. These cooling systems could improve comfort and performance [80]. At present, no commercially available cooling system has been introduced to resolve thermal discomfort with prostheses. Fang et al., during analytical and experimental research, designed a fan-based cooling system for a person with transtibial amputation [32]. Their system aimed to remove heat around the prosthetic liner by improving ventilation inside the prosthetic socket [32]. A brief search in patent databases revealed some registered patents for resolving heat and/or perspiration discomfort inside prostheses [81–83]. These patents are mainly related to design and manufacture of fluid (vapor, air, liquid) pressurizing and circulating devices or application of thermoelectric peltier effect cooling systems [81,83]. Some obstacles exist to improving these systems and making them ready to be commercialized.

In the current literature review, due to heterogeneous demographic and methodological characteristics as well as the results of the selected studies, it was difficult to identify the exact prevalence of thermal-related problems. This review, by providing an insight regarding the high prevalence of thermal discomfort with prostheses, could promote future studies on different aspects of the problem. These include identifying how soft tissue responds to the thermal environment of prostheses, how temperature is distributed on the skin surface of the residual limb at different amputation levels, which materials are more suitable for prosthesis construction, which outcome measures should be used for evaluation of thermal-related discomfort in the population with amputation, and which temperature regulatory systems should be designed for resolving the problem.

CONCLUSIONS

People with amputation deal with thermal stresses in their daily activities, and in spite of great technological advances in the field of prosthetics, current prostheses are unable to resolve these stresses. Thermal stresses inside the prosthetic socket, in addition to decreased quality of life and prosthesis use, comfort, and satisfaction, could endanger people with amputation with risks of skin problems. Thermal discomfort could disturb socket comfort and general satisfaction with prosthesis use. Due to the importance of thermal discomfort inside prostheses, this review was conducted to provide general insight regarding the prevalence of this problem. Out of 38 reviewed studies, 27 identified the prevalence of heat and/or perspiration discomfort inside prostheses. Based on the pooled participant data from these studies, more than 53 percent of people with amputation complained about thermal discomfort inside prostheses, regardless of their prosthesis type or level of amputation. Considering the high prevalence of heat and/or perspiration discomfort with prostheses, it is suggested that an ideal prosthetic socket, besides the socket and residual-limb stability and weight-bearing comfort, should have the ability to control the residual-limb temperature and moisture. Prosthesis thermal discomfort, as a long-lasting and unresolved problem, needs more attention from researchers, clinicians, and prosthetic component manufacturers on thermal-related biomechanics of residual-limb soft tissues, proper fabrication technique, and material selection and introduction of efficient thermoregulatory systems.

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