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ORIGINAL ARTICLE

Comparison of skin perfusion response with alternating and constant pressures in people with spinal cord injury

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Study design: Two-way factorial mixed design, the between-subjects factor as the spinal cord injury (SCI) status (SCI and non-SCI) and the within-subjects factor as the pressure pattern (alternating and constant pressures).
Objectives: To compare the effects of alternating and constant pressures on weight-bearing tissue perfusion in people with SCI, with application for improving alternating pressure support surface usage.
Setting: University research laboratory.
Subjects: A total of 28 participants were studied, 7 participants with cervical injury, 7 participants with injury below T6 and 14 healthy controls.
Methods: Sacral skin perfusion was continuously measured using laser Doppler flowmetry under 10 min preloading, 20 min loading (alternating or constant pressures) and 10 min postloading. Alternating pressure was applied with low-interface pressure at 0 mm Hg and high-interface pressure at 60 mm Hg with a cycle time of 5 min; constant pressure was applied with interface pressure at 30 mm Hg.
Results: The results showed that pressure pattern affects skin perfusion responses in weight-bearing tissues ($P<0.01$). Alternating pressure stimulates an increase in skin perfusion (1.21 ± 0.08 au) as compared with constant pressure (0.74 ± 0.07 au) in people with SCI ($P<0.01$). There was no overall difference in the skin perfusion responses of patients with SCI as compared with non-SCI patients ($P>0.05$).
Conclusion: This study has shown that alternating pressure enhances the skin perfusion of weight-bearing tissues as compared with constant pressure in people with SCI. The protocol tested in this study may be used to guide the selection of parameters of commercial alternating pressure support surfaces for preventing pressure ulcers in people with SCI.
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Keywords: alternating pressure; blood flow; pressure ulcer; spinal cord injury; support surface

Introduction

Pressure ulcers have a significant impact on the quality of life, morbidity, mortality and overall health-care costs in people with spinal cord injury (SCI).[1] Because of increased life expectancy, the incidence of pressure ulcers in the SCI population has increased substantially in recent years. The need for more research on the prevention of pressure ulcers in people with SCI has been indicated by a recent systemic review.[2]

The development of pressure ulcers initiates from a prolonged unrelieved pressure with a subsequent reduction of supply of perfusion and nutrients to local cells.[3] Below a certain threshold, soft tissue responds to ischemia through several vasodilatory mechanisms, including reactive hyperemia, pressure-induced vasodilation (PIV) and thermally induced vasodilation.[4] Beyond that threshold of tolerance in soft tissue, an irreversible ischemic tissue injury forms, resulting in pressure ulcers. As the magnitude of interface pressure cannot be reduced to below the occlusion pressure of arteriolar blood vessels, periodic pressure-relieving activities have been recommended to reduce the duration of interface pressure to enhance tissue perfusion and viability.[5] Kosiak hypothesized that a support surface with intermittent pressure relief functions would reduce the duration of exposure to pressure, thus maintaining ischemic stress within the tolerance of soft tissue. The concept was adopted for the development of alternating pressure support surface (APSS).[6]

Alternating pressure describes a support surface feature in which pressure distribution is periodically altered. The concept of APSS is to reduce the duration of tissue ischemia

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and manipulate the stress and strain within the bulk tissues, thereby eliciting local vasodilatory mechanisms (for example, metabolic or myogenic control) for enhancing tissue viability.[7] Such intervention is particularly beneficial for people with SCI, because these associated local vasodilatory mechanisms are intact even after SCI. Theoretically, a proper setting of operating parameters and configurations for APSS can greatly reduce the risk for pressure ulcers in the SCI population. Although the concept of alternating pressure is promising, previous research has not clearly established the efficacy of alternating pressure, nor has it provided explanations for relevant physiological compensatory mechanisms.[7] The improper settings of alternating pressure parameters (for example, cycle time and inflation and deflation pressure of air bladder) may not benefit weight-bearing tissues, which may partly contribute to the inconsistent efficacies of using APSS on preventing pressure ulcers.[2,8]

To improve the understanding of physiological benefits associated with alternating pressure, several researchers investigated skin perfusion and oxygenation response to commercial APSS.[9,10] Such a design may not be appropriate to understand the mechanism of skin perfusion response to alternating pressure, given that perfusion regulation is transmural pressure dependent.[11] The concept of transmural pressure is important because the microvascular response is dependent on the actual pressure across the blood vessels (that is, transmural pressure = extra luminal pressure − intraluminal pressure).[11] In addition to mechanical factors (transmural pressure), several other factors also contribute to the regulation of microcirculation.[12] The use of commercial APSS to examine skin perfusion response causes an unpredictable interface pressure because of variations in the participant's body weight and body geometric shape.[13] As blood perfusion response is a pressure-dependent response, such a design will not be able to determine the optimal alternating pressure parameters.[7] Jan *et al*. showed that under the same loading pressure, soft tissue has a higher blood perfusion value with alternating pressure loading pattern, compared with the constant loading pressure pattern. The authors concluded that an increase in blood perfusion could reduce the risk for pressure ulcers. However, whether alternating pressure can stimulate an increase in skin perfusion of weight-bearing tissues in people with SCI remains unclear.

The primary goal of this study was to examine the effect of alternating pressure on skin perfusion in people with SCI. We hypothesized that, in people with SCI, alternating pressure, as compared with constant pressure, stimulates an increase in skin perfusion during the loading period. The results from this study may provide a basis for determining a proper setting of APSS for enhancing tissue perfusion in people with SCI.

Methods

Participants

A total of 28 participants were recruited into the study, including 14 participants with SCI and 14 healthy controls, from the university medical center. Of the people with SCI, seven had cervical injury and seven had injury below T6; all had a sedentary lifestyle. The demographic data and injury information of the cervical group were as follows (values are mean ± standard deviation): age, 36.7 ± 10.7 years; body mass index, 23.3 ± 4.8 kg m^{-2}; duration of injury, 6.0 ± 4.5 years; 7 males; 5 people with traumatic injury and 2 people with disc herniation. The demographic data and injury information of the below-T6 group were as follows: age, 39.9 ± 11.4 years; body mass index, 26.2 ± 3.7 kg m^{-2}; duration of injury, 10.1 ± 11.4 years; 7 males; all people with traumatic injury. Body height and weight were self-reported by the participants with SCI. Demographic data of the healthy control were as follows: age, 29.2 ± 9.9 years; body mass index, 23.8 ± 5.4 kg m^{-2}; 5 males. The study was approved by the University Institutional Review Board. The volunteers with SCI were recruited from an SCI research participant registry maintained by the University Model SCI Care Center. Non-SCI participants were recruited from the students and staff of the college. Informed consent was obtained from each participant before any testing. Exclusion criteria included the presence of pressure ulcers, diabetic mellitus, cardiopulmonary diseases, occurrence of spinal cord injury less than 6 months before or use of any medication that may affect cardiopulmonary function. The room temperature was controlled around 24 °C. The variation in room temperature was within 2 °C. The participant stayed in the laboratory for at least 30 min to acclimatize to the room temperature before the start of experimental procedures.

Instrumentation

Laser Doppler flowmetry (LDF) (BPM^2 and P-435 probe, Vasamedics, Eden Prairie, MN, USA) was used to measure skin perfusion. The LDF device delivered a low-power beam (2 mW) of helium–neon laser light (780 nm wavelength) to the skin over the sacrum. The analog output of the LDF device was sampled at 20 Hz using a 16-bit data acquisition card (PCI-MIO-16XE, National Instruments, Austin, TX, USA). According to the literature, the test-retest reliability of laser Doppler measurements ranges from 0.74 to 0.96.[14–16]

A computer-controlled indenter was used to apply alternating and constant pressures on the skin over the sacrum. The location was on the skin of the middle point between the right posterior superior iliac spines and the spinal process. The level of spinal process was determined by a line across the right and left posterior superior iliac spines. The indenter was mounted on a stand that allowed for adjustment with 5 degrees of freedom to allow the indenter head to approach perpendicularly to the skin surface (Figure 1). The indenter head was placed on the skin of the testing site with very gentle pressure. The indenter control program was then activated to maintain interface pressure at 0–3 mm Hg to allow proper contact of the probe and skin. A force feedback control was used to minimize the influences of the participant's unwanted movements. Indentation force was measured along the vertical axis of the indenter using a strain gauge instrumented cantilevered beam. The diameter

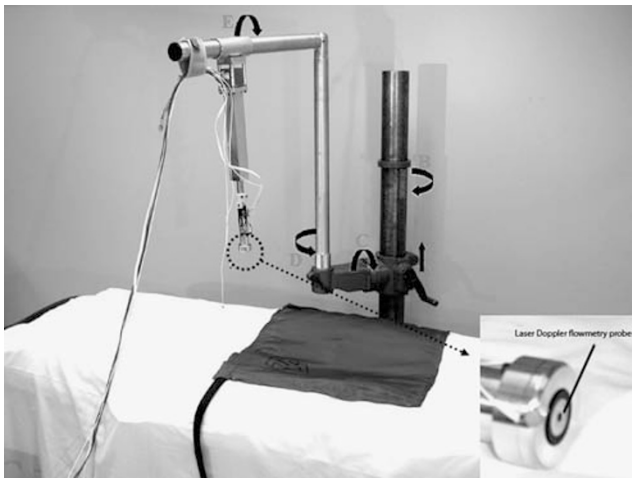

Figure 1 Photograph of the computer-controlled indenter system with a compound sensor head, positioning table and pressure mapping system A, B, C, D and E shown in the figure indicate the degrees of freedom for adjustment. The laser Doppler flowmetry probe is embedded in the central area of the indenter head.

of the indenter head is 36 mm. Detailed information about the indenter can be found in our previous publication.[17]

Loading protocols

The criteria used to develop the loading protocols were based on the literature that shows an increase of perfusion in response to pressure and settings of commercial support surfaces. The parameters included high and low pressures of alternating pressure, cycle time and an appropriate total testing time. The protocol needs to be achievable by current support surface technology. In the literature, pressures between 30 and 70 mm Hg have been shown to result in a PIV.[7,10,18] Thus, we selected 60 mm Hg for the high pressure of AP. The low pressure of AP was selected as 0 mm Hg to allow reactive hyperemic response.[19] To compare the effects of loading patterns (for example, alternating versus constant) on tissue viability, constant pressure was determined to be 30 mm Hg (same average pressure with alternating pressure protocol). The above studies also showed that a 20 min period was required for a PIV. The cycle time was 5 min based on the setting of most commercial products. Cycle time consists of the high-pressure and low-pressure phases. In this study, a total of four cycles of alternating pressure were tested during the 20 min loading period. A time period of 10 min was allowed for preloading and 10 min for postloading. The LDF probe is embedded in the central region of the indenter head to allow the measurement of skin perfusion under loading. The order of alternating and constant pressures was randomly assigned to the participant. A balanced design was selected for this study, that is, half of the participants started from the alternating pressure protocol and the other half started from the constant pressure protocol. Between the two protocols, there was a wash-out period of 30 min.

Data and statistical analysis

A two-way factorial mixed design was used to examine the hypotheses. The dependent variable was sacral skin perfusion. The two independent variables were SCI status (SCI or non-SCI, independent factor) and pressure patterns (alternating or constant pressure, repeated factor). The two main effects were the influences of pressure pattern in skin perfusion response and the influences of SCI status (SCI or non-SCI) in skin perfusion response. Statistical analysis was performed using SPSS 16 (Chicago, IL, USA). Repeated measures analysis under the general linear model was chosen to implement the two-way factorial mixed design. The SCI status was assigned as the between-subjects factor with two levels (SCI and non-SCI); the pressure pattern was assigned as the within-subjects factor with two levels (alternating and constant pressures). Skin perfusion was assigned as the dependent variable. Skin perfusion responses were normalized to the mean of baseline perfusion.[14] To study the influences of the level of spinal injury, we further divided people with SCI into two groups: cervical and below T6. The significance level was set at $P<0.05$.

Results

Figure 2 shows an example of skin perfusion under the high-pressure and low-pressure phases of alternating pressure protocol. Skin perfusion shows a decrease under high pressure and an increase under low pressure.

Mixed-factorial analysis showed that pressure patterns affect the blood perfusion response, that is, alternating pressure enhances skin perfusion as compared with constant pressures. In this study, normalized sacral skin perfusion showed a significant difference under alternating and constant pressures in both, people with SCI and healthy controls ($P<0.01$) (Figure 3). Alternating pressure stimulates an increase in skin perfusion (1.21 ± 0.08), compared with constant pressure (0.74 ± 0.07), in people with SCI ($P<0.01$).

Mixed-factorial analysis showed that SCI status does not affect skin perfusion response, that is, both SCI and non-SCI show the same skin perfusion response to loading pressure ($P>0.05$). Both people with SCI and non-SCI controls showed lower skin perfusion under constant pressure and higher skin perfusion under alternating pressure.

The interaction effect between pressure patterns and SCI status was significant during the loading period ($P<0.05$), which means type of pressure interacts with SCI status on skin-blood-flow response. In our results, people with SCI showed more decline in perfusion under constant pressure and more increase under alternating pressure, compared with healthy controls. During the recovery period, there were no main and interaction effects on skin perfusion responses ($P>0.05$) (Figure 4).

The sacral skin blood data are presented in three groups (cervical, below T6 and healthy) for further comparison (Table 1). No significant difference was found between cervical and below-T6 groups ($P>0.05$).

Discussion

We showed for the first time that alternating pressure stimulates an increase in skin perfusion of weight-bearing

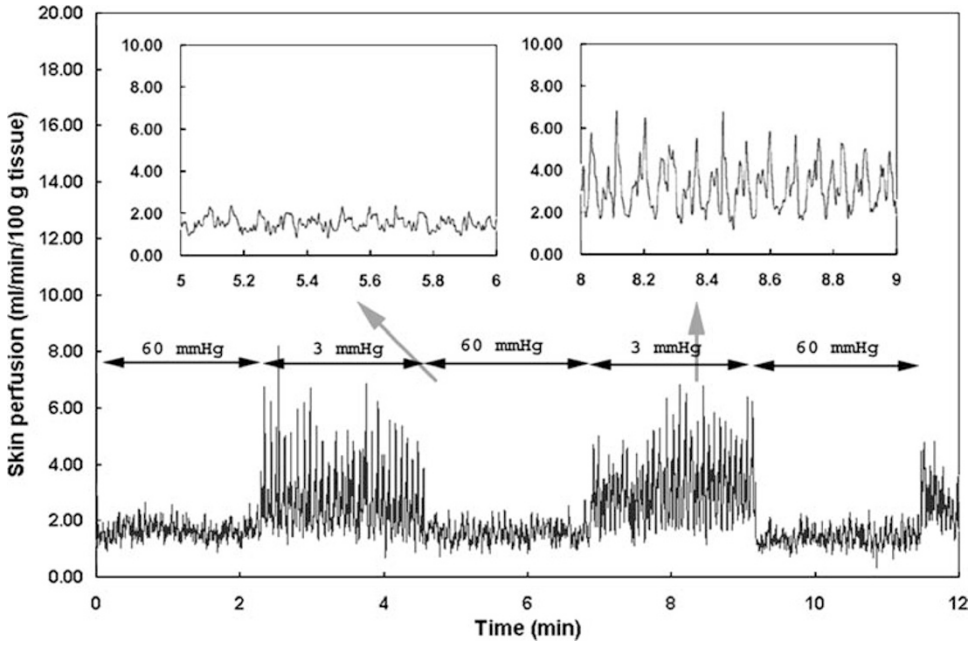

Figure 2 The figure shows skin perfusion under the high-pressure and low-pressure phases of alternating pressure protocol. Skin perfusion shows a decrease under high-pressure phase and an increase under the low-pressure phase. Skin perfusion shows the oscillatory pattern, with smaller oscillatory amplitudes under high pressure and larger amplitudes under low pressure.

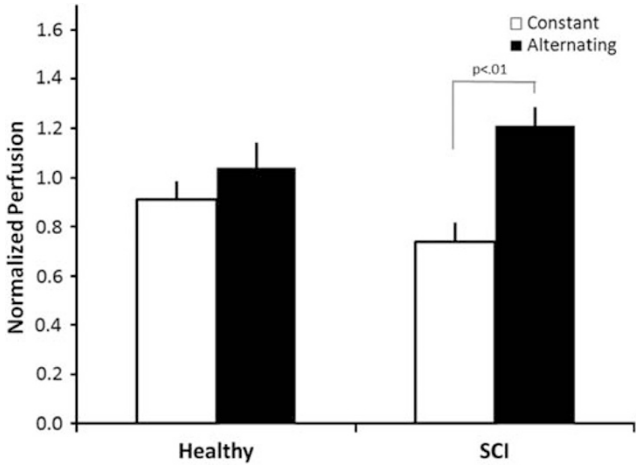

Figure 3 A comparison of mean sacral skin perfusion response to alternating and constant pressures during the loading period. The results indicate that alternating pressure enhances skin perfusion as compared with constant pressure ($P<0.01$). Skin perfusion response was normalized to the mean of baseline perfusion. Values are mean ± s.e.

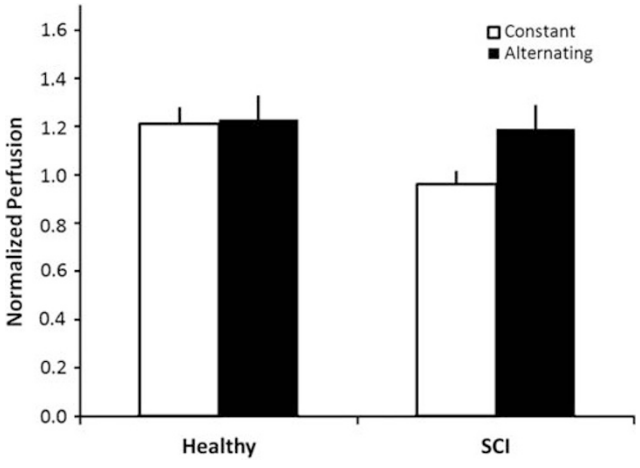

Figure 4 A comparison of mean sacral skin perfusion response to alternating and constant pressures during the recovery period. Skin perfusion response was normalized to the mean of baseline perfusion. Values are mean ± s.e.

tissues as compared with constant pressure in people with SCI. This finding supports the concept of using APSS to reduce the risk of pressure ulcers in the SCI population. The protocol tested in this study (alternating pressure at either 60 or 0 mm Hg and cycle time at 5 min) is achievable by most commercial APSSs. These findings may provide a basis for the selection of alternating pressure parameters to enhance skin perfusion in people with SCI.

Under the 30 mm Hg constant pressure, people with SCI showed a larger decrease in skin perfusion as compared with

Table 1 Mean sacral skin perfusion response to alternating and constant pressures during loading and recovery periods in three groups

	Cervical	*T6 below*	*Controls*
Loading			
Constant	0.68 ± 0.08	0.80 ± 0.12	0.91 ± 0.07
Alternating	1.15 ± 0.11	1.27 ± 0.12	1.04 ± 0.1
Recovery			
Constant	0.95 ± 0.07	0.96 ± 0.1	1.21 ± 0.07
Alternating	1.14 ± 0.13	1.25 ± 0.17	1.23 ± 0.1

Skin perfusion response was normalized to the mean of baseline perfusion. Values are mean ± s.e.

healthy people. This finding implies that a smaller interface pressure is needed to cause tissue ischemia in people with SCI. This is consistent with previous research findings.[18,20] Tissue ischemia occurs when interface pressure exceeds arteriolar blood pressure.[5] People with SCI have a lower systemic blood pressure, including a lower arteriolar and capillary blood pressure;[21] thus, a lower pressure is needed to occlude blood vessels. Furthermore, people with SCI have thinner skin and atrophied muscles, which may aggravate the tissue viability in this population.[18]

Our study confirmed that alternating pressure could be used to enhance skin perfusion in weight-bearing tissues in people with SCI. Although the mechanisms associated with this vasodilatory response to alternating pressure requires further investigation, two physiological responses may be involved in this protective response, namely, reactive hyperemia and PIV.[7] PIV is a phenomenon in which skin -blood -flow increases under a certain range of locally applied pressure.[22] The mechanism is associated with the activation of capsaicin-sensitive nerve fibers, leading to the release of vasodilators to induce smooth muscle relaxation. The PIV is a totally distinct response compared with reactive hyperemia, which is an increase in blood flow after the removal of externally applied pressure. In this study, we postulate that PIV might contribute to an increase in skin -blood -flow under alternating pressure. In addition, both of these mechanisms are local regulatory controls; they can operate and respond to mechanical stress without innervation and their response can be enhanced by the presence of the central nervous system.[23] This implies that people with SCI still express hyperemic response to stimuli but at a weaker level. It has been shown that a full vasodilatory response is required for the presence of neurogenic modulation.[24] The exact influences of SCI, especially of autonomic injury, on vasodilatory response require investigation.[25]

The interaction effects existed between the loading patterns (alternating and constant pressures) and SCI status (presence or not) on the basis of our data. In this study, people with SCI had higher tissue viability under alternating pressure as compared with healthy people; but healthy people showed higher tissue viability under constant pressure as compared with the SCI group. This finding further supports our concept of an individualized support surface. To further examine this concept, researchers may need to study the influences of residual autonomic nervous system function in people with SCI in skin perfusion response to alternating pressure.

In this study, we showed that people with SCI showed a larger increase in skin perfusion as compared with healthy people under alternating pressure. This difference may be explained by the principle of reactive hyperemia—the larger the stimulus the larger the response in the same person.[26] It implies that the applied alternating pressure protocol may be perceived as a smaller stimulus in healthy people than in people with SCI. This is supported by our finding regarding skin perfusion under constant pressure loading, in which healthy people show a smaller decrease in perfusion under loading. Considering these principles, it is reasonable to expect a larger increase in people with SCI than in healthy people under the alternating pressure protocol. To incorporate these phenomena into the design of APSS, the level and completeness of SCI should be considered.

During the recovery period, the time-series data of perfusion showed that reactive hyperemia subsides within 10 min after a 20 min loading. This indicates that the applied pressure did not cause harm to the sacral soft tissues in people with SCI. It is recognized that time to recovery of reactive hyperemia can be used to assess the severity of loading pressure.

In this study, we did not observe a statistical difference in skin perfusion responses between people with injuries above T6 and those with injuries below T6. Theoretically, people with injury below T6 have adequate sympathetic innervation to the cardiovascular system and should be more viable than people with injury above T6.[21] Our findings may be attributed to patient characteristics, including patients with both complete and incomplete spinal injuries. As our long-term goal is to use APSS to prevent pressure ulcers in people with SCI, we intended to recruit people with SCI at various levels and degrees of completeness to prove the concept. In addition, the current classification of completeness refers to sensory and motor functions rather than to autonomic function. However, it is the residual autonomic function after SCI that really affects skin perfusion response to interface pressure. A task force is working to develop methods to quantify autonomic functions following SCI.[25] These assessments may help classify people with SCI in order to achieve a better design to study the effects of SCI on skin perfusion response to alternating pressure.

Clinical application

Clinically, periodic pressure relief is a theme of pressure ulcer prevention that can be achieved through clinicians adjusting patients' posture and patients performing push-up or forward leaning, or by power wheelchair recline and tilt-in-space functions changing weight-bearing sites.[6] However, such pressure relief strategies may not be appropriate or even possible for many at-risk people, especially in people with SCI. These shortcomings may be overcome by alternating pressure technology.[4] Our finding shows the feasibility of using APSS to prevent pressure ulcers in people with SCI. Our findings indicate that alternating pressure parameters at 60 mm Hg for high pressure and at 0 mm Hg for low pressure with a 5 min cycle time may probably enhance tissue viability in people with SCI. This setting is achievable in most commercial APSSs. However, further studies are needed to confirm whether alternating pressure technology can be used to prevent pressure ulcers.

The use of alternating pressure technology for enhancing blood perfusion needs to consider a potential adverse effect associated with the repetitive loading or unloading processes.[7] Such alternating pressure cycles may cause ischemia reperfusion injury. The method of determining whether ischemia reperfusion injury occurs is by assessing the free radicals level, although the specific mechanism remains to be studied.[27] In general, the time of ischemia needed to induce ischemia reperfusion injury is much longer than the

alternating pressure cycle (5 min) tested in this study.[28] Our protocol is more similar to the preconditioning ischemia protocol, which is used to minimize the damage associated with ischemia reperfusion injury. Nevertheless, the time of ischemia reperfusion cycle needed to cause reperfusion injury of the skin and deeper muscles requires further studies.

Study limitation

There are limitations of this study. First, we recruited participants with complete and incomplete SCI in this study. Future research may need to study the influences of completeness of spinal injury, including autonomic, motor and sensory components, in skin perfusion response. Second, tissue viability was assessed at the skin level instead of at the skeletal muscle level. Although the first site of pressure ulcers may develop at the level of deeper tissues (for example, skeletal muscle) instead of at the skin level, we still consider our approach of assessing skin perfusion response to alternating pressure to be highly relevant to the prevention of pressure ulcers in the SCI population. Using laser Doppler flowmetry, only skin perfusion could be measured. However, if a novel technique could provide a noninvasive monitoring of microcirculation within skeletal muscles, we consider that our finding could be reproduced, given that the same perfusion regulatory mechanisms operate in the skin as in the muscles. The third limitation is the small sample size of this study. Our study should be confirmed in larger samples.

Conclusion

We showed that alternating pressure enhances skin perfusion of weight-bearing tissues as compared with constant pressure in people with SCI. This finding supports the concept of using alternating pressure technology to enhance skin perfusion, which may reduce the risk for pressure ulcers in the SCI population. Our findings provide a foundation for determining a proper setting of alternating pressure for enhancing tissue viability in people with various levels of spinal injury.

Conflict of interest

The authors declare no conflict of interest.

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