Measuring Tissue Perfusion During Pressure Relief Maneuvers: Insights Into Preventing Pressure Ulcers

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Abstract

Background/Objective: To study the effect on tissue perfusion of relieving interface pressure using standard wheelchair pushups compared with a mechanical automated dynamic pressure relief system.

Design: Repeated measures in 2 protocols on 3 groups of subjects.

Participants: Twenty individuals with motor-complete paraplegia below T4, 20 with motor-complete tetraplegia, and 20 able-bodied subjects.

Methods: Two 1-hour sitting protocols: dynamic protocol, sitting configuration alternated every 10 minutes between a normal sitting configuration and an off-loading configuration; wheelchair pushup protocol, normal sitting configuration with standard wheelchair pushup once every 20 minutes.

Main Outcome Measures: Transcutaneous partial pressures of oxygen and carbon dioxide measured from buttock overlying the ischial tuberosity and interface pressure measured at the seat back and buttocks. Perfusion deterioration and recovery times were calculated during changes in interface pressures.

Results: In the off-loading configuration, concentrated interface pressure during the normal sitting configuration was significantly diminished, and tissue perfusion was significantly improved. Wheelchair pushups showed complete relief of interface pressure but incomplete recovery of tissue perfusion.

Conclusions: Interface pressure analysis does not provide complete information about the effectiveness of pressure relief maneuvers. Measures of tissue perfusion may help establish more effective strategies. Relief achieved by standard wheelchair pushups may not be sufficient to recover tissue perfusion compromised during sitting; alternate maneuvers may be necessary. The dynamic seating system provided effective pressure relief with sustained reduction in interface pressure adequate for complete recovery of tissue perfusion. Differences in perfusion recovery times between subjects with spinal cord injury (SCI) and controls raise questions about the importance of changes in vascular responses to pressure after SCI.

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Key Words: Pressure ulcers; Prevention; Wheelchairs; Tissue perfusion; Spinal cord injuries; Dynamic seating

INTRODUCTION

Development of serious tissue breakdown at pressure points such as the ischium and coccyx caused by prolonged sitting affects nearly 50% of the 1.4 million

people (1–5) who rely on wheelchairs for mobility. Absence of an effective and reliable pressure relief (6–11) method is thought to be one of the major reasons for the continued high incidence of pressure ulcers among people with spinal cord injury (SCI). Although the optimal treatment strategy for pressure ulcers is prevention, no prevention strategies have proven effective (12).

Pressure ulcer formation is the most common secondary condition among individuals with SCI (13,14), caused in part by an intrinsic physiologic

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derangement (11), with a reduced vascular response to loading, reduced muscular tone, progressive loss of muscle bulk, and impaired sensory biofeedback systems (7,9,11).

A number of risk factors have been cited for pressure ulcer formation, of which pressure concentrated over bony prominences (10,15,16) is thought to be the single most important etiologic factor. Prolonged high pressure results in local tissue ischemia, which is associated with local perfusion failure of nutritive capillaries and leads to tissue necrosis (4,17–19). Furthermore, sustained elevated pressure leads to impaired lymphatic and venous circulation in the compressed tissue, resulting in an accumulation of toxic intracellular materials (20). Short-term loading produces elastic deformation and rapid elastic recovery, whereas long-term loading requires significant time for complete tissue recovery.

Because treatment of established pressure ulcers is difficult and costly, the ideal solution is prevention (21). Current prevention strategies emphasize intermittent relief of interface pressure, such as performing wheelchair pushups every 20 minutes (22,23). This method has proven effective in preventing development of pressure ulcers in some persons (19,24,25). However, various factors limit compliance with these regimens. Merbitz et al (26) found that only 57% of inpatients develop and maintain adequate pressure relief behaviors, and Fisher and Patterson (27) reported that one third of subjects are not compliant with the prescribed regimen at home.

Measurement of interface pressures during the evaluation of wheelchair cushions and seating system is a common practice. However, interface pressure measurements only provide information regarding pressure distribution in various postures and effectiveness of pressure reduction during pressure relief maneuvers. Moreover, several factors prevent interface pressure from being the sole reliable index of the risk of tissue overload. Not only the absolute value of interface pressure varies from person to person, but also the variation of the tissue composition at high-risk locations may accordingly determines the varying capability for soft tissues to sustain pressure load. In this sense, a universal value of interface pressure threshold to determine tissue breakdown risk means little. It has been proposed by several groups (28,29) that interface pressure should be used in conjunction with other measures, such as tissue perfusion, skin temperature, and humidity.

There is limited information about the effect of pressure relief maneuvers on tissue perfusion (30). Transcutaneous tissue perfusion has been used as the index of tissue viability by several groups (1,7,31–33). From the early work of Seiler et al (32,33), a baseline of transcutaneous tissue oxygen ($tcPO_2$) value for uncompressed soft tissue was established as 80 mmHg (10.7 kPa). When tissue is subjected to pressure load, the $tcPO_2$ decreases dramatically because of the occlusion of the blood flow underneath the pressure point. Bogie et al (1)

suggested a threshold value of $tcPO_2$ as 30 mmHg to indicate a significantly higher risk to tissue viability below this value. In their later study, Bogie et al (7) also suggested the threshold value for $tcPCO_2$ as 44 mmHg.

The purpose of this study was to evaluate the effects on tissue perfusion of a mechanical method of automated pressure relief using a seating system that intermittently reduces ischial load by tilting the back part of the seat down 20° every 10 minutes compared with standard wheelchair pushups.

METHODS

Subjects

Twenty men with paraplegia (age, 35.1 ± 6.9 years; weight, 87.2 ± 18.5 kg; height, 180.0 ± 7.6 cm; height range, 162.6–188.0 cm; body mass index [BMI], 27.0 ± 6.0 kg/m²; postinjury, 8.4 ± 6.1 years; motor complete) with injury level lower than T4, 20 subjects with tetraplegia (age, 36.5 ± 10.0 years; weight, 81.8 ± 16.1 kg; height, 176.9 ± 9.1 cm; height range, 154.9–195.6 cm; BMI, 26.4 ± 6.0 kg/m²; postinjury, 9.2 ± 9.5 years; motor complete; 5 women and 15 men), and 20 able-bodied subjects (age, 39.3 ± 14.8 years; weight, 71.3 ± 20.3 kg; height, 169.9 ± 12.8 cm; height range, 149.9–188.0 cm; BMI, 24.4 ± 4.6 kg/m²; 10 women and 10 men) were tested. The inclusion criterion for those with paraplegia was level of injury below T4 and sufficient arm strength to perform arm pushups for pressure relief. The sex disproportion among individuals with SCI can be explained by the low incidence of SCI (18.9%) among women and the high incidence (81.1%) among men as reported by the National SCI Statistical Center (NSCISC) (13). None of the 60 subjects had history of flap surgery in the tested area. Written informed consent following the guidelines of the Institutional Review Board of Northwestern University was obtained before each experiment. The inclusion criteria for paraplegia group included the ability to independently do wheelchair pushups for pressure relief. Individuals with degenerative disorders of the spine and with histories of injury/surgery of the pelvis, hip joint, and thigh, or with hip flexion contractures, were excluded. Also excluded were those with severe pain, spasticity, and psychologic concerns preventing proper cooperation.

Wheelchair and the Intelligent Pressure Ulcer Prevention Cushion Seating System

A wheelchair equipped with an intelligent pressure ulcer prevention cushion (iPUPc) seating system was used for all tests. The iPUPc seating system consists of a split seat and a backrest with an enhanced lumbar support. The wheelchair was set up with the seat parallel to the floor, and the seat back reclined 5° from perpendicular to the seat. The split seat has a movable posterior part of the seat, which is one third of the seat depth from the rear end and can be tilted downward (20°) to reduce the contact between the user's buttocks and the seat (Figure

Figure 1. The wheelchair equipped with the iPUPc seating system. The iPUPc seating system consisted of a split seat and a backrest with an enhanced lumbar support. The split seat had a movable back part of the seat that could be tilted downward (20°) to release the contact between the user's ischia and the seat. The backrest hosted an inflatable air pouch as an adjustable lumbar support. The wheelchair is shown in the normal sitting (A) and off-load configurations (B). Three light-color straps on the seat are for clearly showing the tilting of the back part of the seat. At the left bottom corner of each figure, the average interface pressure on the seat cushion corresponding to normal sitting and off-load configurations is given. These interface pressure maps were the average map for the 20 control subjects. The method dividing the seat cushion for interface pressure data processing is also shown. Posterior-Seat, from the rear edge of the seat to the buttock-thigh fold; Middle-Seat and Anterior-Seat, equal divisions of the area between the buttock-thigh fold to the front edge of the seat.

1). The cushion consists of 2 layers of viscoelastic foam of 1-in thickness. The bottom layer is moderately stiff, whereas the top layer is soft, providing soft body contact while maintaining firm support. The seat height and depth can also be adjusted to accommodate various body builds of the participants. The backrest incorporates an inflatable air pouch as an adjustable lumbar support. Two arm rests, which were adjustable in height, were attached to the wheelchair. A customized system with a microprocessor (Microprocessor; BasicStamp; Parallax, Rocklin, CA) was used to precisely regulate the tilting of the posterior seat section and the inflation/deflation of the lumbar air bladder through a motor and an air pump. The iPUPc seating system alternates the sitting configuration of the wheelchair between 2 sitting configurations: normal sitting and a tilted posterior seat position, referred to as the off-loading configuration.

Proper sitting posture for all aspects of this study included sitting with the buttocks all the way back into

the seat with foot rests adjusted to position the femurs parallel to the floor. The arm rests were adjusted for each subject; however, they were only used when the subject was performing an arm pushup for pressure relief. In addition, the height of the seat back was adjusted so that the lumbar support was in contact with the low back at the level of the iliac crest. Our experience in a previous study (34) indicated that setting the lumbar support at this level supported the lumbar lordosis while not pushing the subject forward. The subject was asked to maintain the posture as consistently as possible during the 2 trials.

Sitting Protocols

Two sitting protocols were compared. The dynamic sitting protocol was defined as sitting configuration alternated between a normal sitting configuration (sitting upright with full seat support and no added lumbar support) and the off-loading configuration (sitting

upright with the posterior seat section tilted down 20° to provide pressure relief to the ischial tuberosities and coccyx and an enhanced lumbar support). Each sitting protocol lasted for 1 hour. The seat position was alternated every 10 minutes. The wheelchair pushup protocol was defined as sitting in the normal sitting configuration and performing a standard wheelchair pushup every 20 minutes. A pushup entailed the subject pushing up on the wheelchair arm rest or wheels enough to lift the buttocks off the seat. Subjects were asked to maintain each pushup as long as they could. Subjects with tetraplegia unable to perform pushups by themselves were provided a pressure relief every 20 minutes by lifting them up off the seat for duration of 60 seconds using a Hoyer lift (Hoyer Hydraulic Patient Lift; Sunrise Medical, Longmont, CO). Because the pressure relief provided to this group of subjects was at a fixed duration of 60 seconds, they were not included in the analysis of the duration of pushups. Control subjects were not included in the data analysis for this protocol.

Interface Pressure

Two Xsensor (Xsensor Technology Corporation, Calgary, Canada) pressure-mapping mats with 36 × 36 cells were secured over the surface of the backrest and the seat before the subject transferred into the wheelchair to record the interface pressure on backrest and the seat with a sampling frequency of 1 Hz.

Tissue Perfusion

TCM3 Oximeters (TCM3 Oximeter; Radiometer A/S, Brønshøj, Denmark) were used to record transcutaneous partial pressures of oxygen (tcPO₂) and carbon dioxide (tcPCO₂) from the sitting area. Electrodes were calibrated using known gases and were attached to the skin overlying right ischial tuberosity (IT), posterior side of right middle thigh (MT), and right distal thigh (DT). To avoid artifacts in interface pressure reading, a soft latex foam ring (Callus Cushions, inner diameter, 15 mm and outer diameter, 35 mm; Walgreens, Deerfield, IL) was placed around each electrode to distribute concentrated interface pressure points caused by the sensors. TCM3 readings of tcPO₂ and tcPCO₂ were fed to a host computer using serial ports with 0.509 Hz. Data collected from Xsensor and Oximeters were synchronized and recorded continuously for the 2 protocols.

Data Processing

Interface pressure. From the interface pressure recordings, total contact area (TCA), average pressure (AP), and peak interface pressure (PP) of both the backrest and the seat were obtained. The TCA was calculated by including only cells with pressure greater than 5 mmHg. For evaluating the interface pressure distribution pattern, the interface pressure reading from the seat was grouped into 3 horizontal regions (Anterior-Seat, anterior; Middle-Seat, middle; Posterior-Seat, posterior). As shown in Figure 1,

the Posterior-Seat was the area between the buttock-thigh fold and the rear edge of the seat. The area anterior to the buttock-thigh fold was bisected into the Anterior-Seat and the Middle-Seat.

Tissue Perfusion. To examine data from both the Oximeters (collected at 0.509 Hz) and the Xsensor (collected at 1 Hz) at the same time points, data from Oximeters were first interpolated to the same sampling frequency as that of the interface pressure, ie, 1 Hz, using a spline algorithm in Matlab 7.0.1 (The Mathworks, Natick, MA).

For each recording site, tcPO₂ and tcPCO₂ were averaged along the recording time for each configuration (normal sitting or off-loading) over the entire protocol. To quantify the tissue perfusion response to the dynamic change of interface pressure during changes between normal sitting and off-loading configurations, perfusion deterioration time and perfusion recovery time were defined as the time taken for the tissue perfusion parameters to reach 90% of the maximum change.

Statistical Analysis

For configuration and protocol effects in each group, a paired *t*-test determined any significant differences in TCA, AP, PP, tcPO₂, and tcPCO₂ between the normal sitting and off-loading sitting configurations, as well as between the dynamic and wheelchair pushup trials. For interface pressure parameters (ie, TCA, AP, and PP) a 1-way ANOVA was performed to detect any group difference among the 3 groups. For tcPO₂, and tcPCO₂, however, a 2-way ANOVA was first performed for group effect and recording location effect (ie, the difference among the recordings from the 3 locations of IT, MT, and DT). When significance of any effect of the 2-way ANOVA was detected, a 1-way ANOVA was run to obtain the *P* values. All statistical tests were performed using SAS software (Version 9.1.3; SAS Institute, Cary, NC) with a significance level of 0.05.

RESULTS

There was no difference in age or BMI among the 3 groups (*P* > 0.05).

Interface Pressure

A similar pattern for interface pressure was seen in all groups. As shown in the example in Figure 1, interface pressure was concentrated within the vicinity of the ITs during normal sitting. When sitting in the off-loading configuration, the thighs took the most load, whereas the ITs were largely relieved from the sitting load. In addition to the TCA and AP plotted in Figure 2, the percentage of change of these interface pressure parameters are given in Table 1 for comparing the values in the off-loading configuration to those from the normal sitting configuration. Data are presented for each seat region (Anterior-Seat, Middle-Seat, and Posterior-Seat) and from each group (control, paraplegia and tetraplegia groups) to

Figure 2. (A) Total contact pressure (TCA, cm²; mean $\pm$ SE) and (B) average pressure (AP, mmHg) for each seat region (Anterior-Seat, Middle-Seat, and Posterior-Seat) in normal sitting and off-load configurations for control, paraplegic, and tetraplegic groups.

show the effectiveness of the off-loading configuration to redistribute interface pressure. Compared with that in normal sitting configuration, the TCA, AP, and PP of the Posterior-Seat significantly ($P < 0.001$) decreased in the off-loading configuration for all groups (Table 1; Figure 2).

Transcutaneous Tissue Perfusion

Average tcPO₂ and tcPCO₂ during normal sitting and off-loading configurations are given in Table 2 for the location at IT and Table 3 for locations at MT and DT. During normal sitting configuration, average tcPO₂ at IT was less than 10 mmHg for all groups. Likewise, average tcPCO₂ at IT was greater than 60 mmHg for all groups. There were significant differences for the tcPO₂ and tcPCO₂ among the 3 recording locations in normal sitting configuration. MT and DT both had significantly higher tcPO₂ and lower tcPCO₂ than those at IT in all groups (Tables 2 and 3). There was no significant group difference for tissue perfusion readings between groups.

In the off-loading configuration, tcPO₂ at IT was maintained above 50 mmHg for all groups, whereas MT

and DT were all greater than 30 mmHg. At the same time, tcPCO₂ at IT was less than 45 mmHg for all groups, whereas that at MT and DT was less than 60 mmHg. No group difference was found for tissue perfusion ($P > 0.05$). Compared with the readings of tissue perfusion in normal sitting configuration, tcPO₂ at IT substantially increased by 5 to more than 20 times in the off-loading configuration for all groups, becoming the highest among the 3 recording sites.

Figure 3 shows representative interface pressure and transcutaneous tissue perfusion continuously recorded from IT for dynamic (Figure 3A) and wheelchair pushup (Figure 3B) protocols. Figure 3A shows the representative data of tcPO₂ and tcPCO₂ recorded from IT during a trial from a subject in the paraplegic group. In this trial, interface pressure and tissue perfusion changed accordingly with changes in sitting postures. In each of the phases of the normal sitting configuration, the average tcPO₂ was very low, and the tcPCO₂ gradually increased substantially from the starting value. In the phases of off-loading configuration, the tcPO₂ maintained a high level, which was much higher than that of the normal sitting

Table 1. Changes of Interface Pressure Parameters (Mean $\pm$ SE) on the Seat When the Sitting Configuration was Switched From Normal Sitting to Off-Load Configuration for the Control, Paraplegia, and Tetraplegia Groups

Group (N = 20)	Anterior-Seat	Middle-Seat	Posterior-Seat
Control			
TCA (%)	0.7 $\pm$ 0.9	3.8 $\pm$ 0.9	−31.5 $\pm$ 2.9
P_{N-R}	>0.05	<0.001	<0.001
AP (%)	12.2 $\pm$ 2.0	39.3 $\pm$ 3.0	−27.6 $\pm$ 5.2
P_{N-R}	<0.001	<0.001	<0.001
PP (%)	21.4 $\pm$ 5.1	35.3 $\pm$ 9.3	−14.2 $\pm$ 5.0
P_{N-R}	<0.001	0.001	0.005
Paraplegic			
TCA (%)	2.7 $\pm$ 1.9	3.8 $\pm$ 0.8	−24.2 $\pm$ 3.1
P_{N-R}	>0.05	<0.001	<0.001
AP (%)	16.2 $\pm$ 2.4	36.3 $\pm$ 4.9	−38.1 $\pm$ 4.0
P_{N-R}	<0.001	<0.001	<0.001
PP (%)	27.7 $\pm$ 5.3	13.1 $\pm$ 6.7	−9.2 $\pm$ 5.1
P_{N-R}	<0.001	0.033	0.043
Tetraplegic			
TCA (%)	1.3 $\pm$ 1.1	−4.5 $\pm$ 1.1	−36.7 $\pm$ 3.6
P_{N-R}	>0.05	<0.001	<0.001
AP (%)	39.0 $\pm$ 3.9	5.3 $\pm$ 5.6	−42.8 $\pm$ 2.4
P_{N-R}	<0.001	>0.05	<0.001
PP (%)	0.4 $\pm$ 0.4	−0.1 $\pm$ 0.1	−50.7 $\pm$ 3.9
P_{N-R}	>0.05	>0.05	<0.001

Blue type indicates statistical significance.

P_{N-R} P value of configuration effect between normal sitting and off-load configurations.

phases. The $tcPCO_2$ was at a low level compared with the normal sitting phases. In comparison, AP in the posterior region of the seat showed little change during the entire wheelchair pushup trial (Figure 3B), except during the time when the subject was performing a pushup. After the trial started, $tcPO_2$ quickly dropped to almost zero and minimally increased for a brief period of time during each pushup, whereas $tcPCO_2$ increased gradually to a high level and dropped a small amount each time a pushup was performed.

Table 2 summarizes the tissue perfusion data at IT during each phase (normal sitting, off-loading configuration, or pushup) over the entire 1-hour trial for both protocols. All subjects had very low $tcPO_2$ levels (<10 mmHg) and elevated $tcPCO_2$ (>60 mmHg) during the normal sitting configuration with measures of $tcPO_2$ and $tcPCO_2$ not significantly different among the groups. During the off-loading configuration phases, $tcPO_2$ increased dramatically in all groups to greater than 50 mmHg and $tcPCO_2$ decreased to less than 45 mmHg in all groups, indicating a complete recovery of tissue perfusion while in the off-loading configuration. However, during pushups, $tcPO_2$ at IT increased and $tcPCO_2$ decreased only slightly, indicating incomplete recovery of tissue perfusion.

Tissue Perfusion Recovery and Deterioration Time

Figure 4 summarized the results of average perfusion recovery time and perfusion deterioration time for the 3 groups.

During interface pressure release achieved by changing from the normal sitting configuration to the off-loading configuration, average perfusion recovery time was 200 to 250 seconds (control: 197.8 $\pm$ 10.4 [SD] s, paraplegic: 208.8 $\pm$ 7.9 s, and tetraplegic: 214.4 $\pm$ 4.5 s) for $tcPO_2$ for all 3 groups. There was no group difference among the 3 groups for perfusion recovery time of $tcPO_2$. However, significantly shorter perfusion recovery time for $tcPCO_2$ was found in the control group than the 2 SCI groups (control: 202.8 $\pm$ 10.4 s, paraplegic: 251.8 $\pm$ 9.2 s, and tetraplegic: 254.6 $\pm$ 8.9 s; $P < 0.001$).

During interface pressure increase, which was caused by changing from the off-loading configuration to the normal sitting configuration, average perfusion deterioration time for $tcPO_2$ was about 200 seconds (control: 198.8 $\pm$ 9.7 s, paraplegic: 202.1 $\pm$ 10.4 s, and tetraplegic: 199.3 $\pm$ 7.6 s) for all groups without group difference, whereas the values of average perfusion deterioration time for $tcPCO_2$ varied substantially between the controls and the SCI groups (control: 322.7 $\pm$

Table 2. Average Tissue Perfusion Levels in tcPO₂ (mmHg) and tcPCO₂ (mmHg) (Means ± SE) Measured From ITs in Normal Sitting and Off-Load Configuration and During Dynamic and Wheelchair Pushup Protocols

Tissue Perfusion	tcPO ₂ (mmHg)	tcPCO ₂ (mmHg)
Control (N = 20)		
Normal sitting	5.0 ± 1.7	71.5 ± 5.8
Off-load	59.6 ± 4.2	44.8 ± 2.7
P_{N-R}	<0.001	<0.001
1-hour dynamic	32.3 ± 2.4	58.1 ± 3.4
1-hour wheelchair pushup	NA	NA
Paraplegic group (N = 20)		
Normal sitting	9.3 ± 3.8	63.2 ± 4.3
Off-load	54.4 ± 4.9	40.6 ± 2.0
P_{N-R}	<0.001	<0.001
1-hour dynamic	31.8 ± 3.5	53.0 ± 3.3
1-hour wheelchair pushup	11.2 ± 4.0	74.3 ± 6.8
$P_{NPUSH-DYN}$	<0.001	<0.001
Pushups	19.1 ± 3.7	62.3 ± 5.8
Tetraplegic group (N = 20)		
Normal sitting	2.2 ± 0.6	72.3 ± 5.9
Off-load	55.0 ± 6.4	42.0 ± 2.9
P_{N-R}	<0.001	<0.001
1-hour dynamic	30.9 ± 3.5	54.5 ± 4.4
1-hour wheelchair pushup	3.2 ± 0.6	79.3 ± 7.0
$P_{NPUSH-DYN}$	<0.001	<0.001
Pushups	14.0 ± 3.7	60.7 ± 4.7

P_{N-R} , P values for comparison between the normal sitting and off-load configurations; $P_{NPUSH-DYN}$, P values for comparison between wheelchair pushup and dynamic protocols; NA, not applicable.

37.2 s, paraplegic: 287.4 ± 24.8 s, and tetraplegic: 279.8 ± 19.4 s), however, without significance.

The average pushup time achieved by the paraplegic group was 49.0 ± 2.8 (SE) seconds (N = 20).

DISCUSSION

This study measured transcutaneous tissue perfusion in 2 sitting configurations (normal sitting and off-loading) and during 2 sitting protocols (dynamic and wheelchair pushup) for able-bodied controls and individuals with paraplegia and tetraplegia. The effect of redistributing interface pressure on tissue perfusion was assessed from these 2 different sitting configurations and 2 sitting protocols. In general, the values of tcPO₂ and tcPCO₂ in the normal sitting configuration, which is similar to the regular sitting posture used in other studies, were comparable to those previously reported (7,31,32,36).

For the off-loading configuration, a distinct pattern of interface pressure distribution was found as substantially repositioning the majority of the sitting load away from the area around ischia and coccyx and moving it to the thighs. This was true for both able-bodied controls and individuals with SCI. Along with this sitting load repositioning, perfusion in buttock tissue experienced

dramatic improvement, as indicated by the 5 to 20 times increase in tcPO₂ and more than 20 mmHg decrease in tcPCO₂ at the ischia, which made the ischia the location with the highest tcPO₂ reading within the buttock-thigh area. Data in this study indicated that tissue perfusion in the buttock area around the ischia can be greatly improved as a result of intermittent load repositioning. Evidence suggests that the thighs can sustain more than 80 mmHg without injury, whereas that value for the ischia is less than 40 mmHg and for the coccyx is only 14 mmHg (37). Therefore, intermittently shifting interface pressure to area with less pressure ulcer risk and higher load-bearing capacity may be a strategy for pressure ulcer prevention.

The advantage of using the iPUPc seating system is that it can provide effective pressure relief during prolonged sitting. Our results show that the dynamic protocol achieved significantly higher perfusion levels within buttock tissue than that of using standard wheelchair pushups. In the wheelchair pushup protocol, pressure relief and perfusion recovery achieved by pushups were minimal and momentary. Our data confirmed the findings by Bader (38) that full recovery of tissue perfusion could not be achieved within 2

Table 3. Average Tissue Perfusion Levels in tcPO₂ (mmHg) and tcPCO₂ (mmHg) (Means ± SE) Measured From Middle Thigh (MT) and Distal Thigh (DT) in Normal Sitting and Off-Load Configurations and During Dynamic and Wheelchair Pushup Protocols

Tissue Perfusion	tcPO ₂ (mmHg)		tcPCO ₂ (mmHg)	
	MT	DT	MT	DT
Control (N = 20)				
Normal sitting	32.0 ± 7.4	42.1 ± 7.6	51.0 ± 3.6	46.0 ± 5.2
<i>P</i> [*]	0.001	<0.001	0.005	0.003
Off-load	53.9 ± 8.1	52.4 ± 6.4	51.0 ± 5.6	43.1 ± 4.5
<i>P</i> [*]	>0.05	>0.05	>0.05	>0.05
<i>P</i> _{N-R}	<0.001	>0.05	<0.001	>0.05
1-hour dynamic	43.0 ± 6.9	47.2 ± 5.9	51.0 ± 3.8	44.6 ± 4.2
<i>P</i> [*]	0.044	0.004	>0.05	0.011
1-hour wheelchair pushup	NA	NA	NA	NA
Paraplegic (N = 20)				
Normal sitting	33.1 ± 4.9	39.2 ± 5.6	48.6 ± 5.4	45.0 ± 3.3
<i>P</i> [*]	<0.001	<0.001	0.013	<0.001
Off-load	43.8 ± 5.2	47.7 ± 5.3	55.9 ± 10.0	44.0 ± 3.0
<i>P</i> [*]	>0.05	>0.05	>0.05	>0.05
<i>P</i> _{N-R}	<0.001	>0.05	<0.001	>0.05
1-hour dynamic	38.4 ± 4.5	43.5 ± 4.4	52.2 ± 7.5	44.5 ± 3.0
<i>P</i> [*]	>0.05	0.021	>0.05	0.032
1-hour wheelchair pushup	30.2 ± 5.7	52.0 ± 7.9	48.6 ± 9.9	40.1 ± 3.8
<i>P</i> [*]	0.007	<0.001	0.021	<0.001
<i>P</i> _{NPUSH-DYN}	<0.001	>0.05	<0.001	<0.001
Pushup	40.4 ± 6.3	49.9 ± 8.6	46.7 ± 10.3	38.8 ± 4.1
<i>P</i> [*]	0.007	<0.001	>0.05	0.002
Tetraplegic (N = 20)				
Normal sitting	41.0 ± 4.8	53.2 ± 6.6	34.1 ± 3.1	34.2 ± 2.7
<i>P</i> [*]	<0.001	<0.001	<0.001	<0.001
Off-load	34.7 ± 7.2	49.5 ± 7.1	37.2 ± 2.7	33.1 ± 2.8
<i>P</i> [*]	0.005	>0.05	0.050	0.010
<i>P</i> _{N-R}	<0.001	>0.05	<0.001	0.047
1-hour dynamic	37.9 ± 5.2	51.4 ± 6.0	35.7 ± 2.5	33.6 ± 2.7
<i>P</i> [*]	>0.05	0.001	0.001	<0.001
1-hour wheelchair pushup	48.9 ± 4.6	54.1 ± 4.9	33.4 ± 2.6	31.0 ± 2.8
<i>P</i> [*]	<0.001	<0.001	<0.001	<0.001
<i>P</i> _{NPUSH-DYN}	<0.001	>0.05	<0.001	0.001
Pushup	50.0 ± 5.0	54.6 ± 4.6	40.4 ± 4.8	31.0 ± 2.7
<i>P</i> [*]	<0.001	<0.001	0.004	<0.001

P^{*}, *P* values for comparison of perfusion parameters between those measured from MT or DT and those from IT; *P*_{N-R}, *P* values for comparison between the normal sitting and off-load configurations; *P*_{NPUSH-DYN}, *P* values for comparison between wheelchair pushup and dynamic protocols; NA, not applicable.

minutes. Theoretically, full tissue perfusion recovery is optimal for pressure ulcer prevention. It follows that the pressure relief should last long enough to allow tissue perfusion recovery and maintain that level of perfusion for a sufficient amount of time. This study showed that the time needed is in the range of 200 to 300 seconds. However, this study does not offer insights into how often these off-loading episodes should occur. It is clear

from our data that wheelchair pushups, with an average pressure relief time of 49 seconds, are far from an adequate duration for total recovery of tissue perfusion. In the dynamic protocol, however, the pressure relieving time was adjustable and it lasted as long as the off-loading phase was maintained. In this way, it is more likely for the dynamic protocol to provide better perfusion recovery.

Figure 3. Representative results of tissue perfusion and AP for dynamic and wheelchair pushup sitting protocols. Data are from 1 subject in the paraplegic group. (A) Tissue perfusion at IT and AP on posterior seat during a trial of Dynamic protocol. (B) Tissue perfusion and AP on posterior seat during a trial of wheelchair pushup protocol.

In this study, transcutaneous tissue perfusion was recorded from the buttock-thigh area in conjunction with the interface pressure measurement to investigate how the repositioning of superficial pressure load induces perfusion reactions in underlying soft tissues. This method provides a mechanism to identify whether pressure relief maneuvers are sufficient to allow tissue reperfusion. From data in this study, when subjects sit in the normal sitting configuration, tcPO₂ level at the ischia fell close to zero for both able-bodied and individuals with SCI. At the same time, the tcPCO₂ at ischia rose to greater than 60 mmHg at all times, which is well above the suggested threshold of 44 mmHg. However, when the subjects sat in the off-loading configuration, which largely reduced the ischia contact (the pressure seen on Posterior-Seat), both the tcPO₂ and the tcPCO₂ readings for the ischia were substantially improved in all groups. The tcPO₂ recovered to levels above 50 mmHg, and the tcPCO₂ was decreased to levels at or below 44 mmHg. This finding confirmed our hypothesis that sitting with reduced ischia contact will significantly improve the blood flow through the area.

Figure 4. Average tissue perfusion recovery time during interface pressure decrease and average tissue perfusion deterioration time during interface pressure increase for control, paraplegic, and tetraplegic groups. The average pushup time achieved by the paraplegic group is also given in A as a comparison to perfusion recovery time. (A) Perfusion recovery time during interface pressure decrease compared with pushup time. (B) Perfusion deterioration time during interface pressure increase.

Dynamic change of tissue perfusion with respect to the interface pressure was also examined in this study. In our experimental protocol, the sitting configuration of the wheelchair was regulated with a microprocessor with position feedback. The tilting angle and speed for the posterior seat was precisely controlled as 20° and 1°/s, respectively. Therefore, results of the perfusion changes over the interface pressure changing period are comparable among subjects. When interface pressure increased, it took the control subjects an average of 35 more

seconds than SCI subjects to reach the highest tcPCO_2 level. During the interface pressure decrease, control subjects achieved perfusion recovery the earliest, with a significantly faster recovery found for their tcPCO_2 . This finding suggests that, in individuals with SCI, the blood flow pattern or the reaction of blood flow to external pressure load in their buttock-thigh area may have been altered.

It was seen in our study that the tcPO_2 level always reacted faster than tcPCO_2 , both for perfusion recovery time and perfusion deterioration time. For perfusion recovery time, it is possibly because that the sudden opening of the blood flow immediately brings in fresh O_2 , whereas it takes time for CO_2 to be expelled. Similarly for perfusion deterioration time, the closure of the blood flow under the pressure immediately stops the supply of the fresh O_2 , whereas the CO_2 would be accumulated gradually. However, another explanation for such phenomenon may exist. Lima and Bakker (39) pointed out that the diffusion constant of CO_2 is about 20 times greater than that of O_2 . Considering our measurement of tissue perfusion was by way of the transcutaneous method, the slow changes we saw for CO_2 might actually be caused by the sluggish response of CO_2 on the skin surface to the real process occurring subcutaneously in the soft tissue.

There are limitations of this study. For transcutaneous tissue perfusion measurement, it is recommended that an electrode of the Oximeter be placed on the subject's chest to setup a baseline reading of this individual. Because of the limited availability of Oximeter units, this reference reading was not taken on any of the participants. However, because the study mainly focused on the effect of 2 different sitting configurations and 2 sitting protocols, each subject was used as his own control in evaluating such effects. Thus, the baseline reading was not absolutely necessary. Another limitation was the sex differences among the groups of subjects; the paraplegic group had only male participants. Although we are not aware of any reported sex differences in the tissue perfusion reaction to mechanical load, findings in this study should be interpreted with caution when applying to any sex-related cases. Future studies should include women with paraplegia because of the potential for a sex difference. In addition, this study evaluated the dynamic sitting protocol only on iPUPc cushions covered with the Rubatex (Rubatex International, Bedford, VA) material; the effect of dynamic sitting on tissue perfusion might not be exactly the same when using some other cushion cover materials. We also found that individuals with tetraplegia tended to use their thighs more to support their body weight when sitting in the chair as shown in Figure 2. However, we do not currently have an explanation for this phenomenon. Further analysis of the data and further research are needed to find the reason.

CONCLUSIONS

The dynamic sitting protocol evaluated in this study had a significant effect on improving tissue perfusion in the buttock area through periodically repositioning the concentrated pressure from buttocks to the thighs. The finding that the interface pressure relief achieved by wheelchair pushups was not sufficient to allow an optimal recovery of the buttock tissue perfusion provides information to clinicians and therapists that some sort of method other than the arm pushup, such as a device assisting in pressure relief, may be needed to ensure adequate prevention of pressure ulcers in individuals with SCI. Results from this study also suggest that a dynamic sitting protocol might be a better option for people sitting for a prolonged time.

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