Spinal Cord (2010) 48, 336–341

www.nature.com/sc

ORIGINAL ARTICLE

Effects of dynamic sitting interventions on tissue oxygenation in individuals with spinal cord disorders

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Study Design: An explorative cross-sectional study.
Objectives: The objective of this study was to investigate the possibility of imposing dynamic sitting behavior on individuals with spinal cord disorders by using the Dynasit chair and to investigate its effect on the (sub-)cutaneous tissue oxygenation.
Setting: Rehabilitation Centre het Roessingh, Enschede, the Netherlands.
Subjects: Ten male subjects with a spinal cord disorder.
Methods: The Dynasit chair, an experimental simulator chair, containing mechanical concepts for postural adjustments, regulation of tuberal load and pelvic rotation, was developed to allow individuals with a spinal cord disorder to sit in a dynamic way. An experiment was carried out in which a dynamic sitting pattern was imposed. The sitting pattern consisted of series of actuated changes in posture, tuberal load and pelvic orientation. Effects of these changes on (sub-)cutaneous buttock tissue oxygenation were investigated by transcutaneous measurement of tissue oxygenation.
Results: Nonparametric statistical analyses were carried out on nine subjects that completed the study. Results showed significant positive effects ($P<0.05$) of actuated changes in tuberal load on the cutaneous and subcutaneous tissue oxygenation.
Conclusion: The Dynasit chair is effective in imposing dynamic sitting behavior in individuals with a spinal cord disorder and consequently might reduce the chance of tissue degradation.
Spinal Cord (2010) **48,** 336–341; doi:10.1038/sc.2009.138; published online 27 October 2009

Keywords: dynamic sitting; pressure ulcers; deep tissue injury; tissue oxygenation; O2C

Introduction

Superficial and deep pressure ulcers (PUs) are common in individuals with spinal cord injury that use a wheelchair for their mobility. It is understood that deep PUs result from prolonged pressure and develop usually near the bony prominences where internal pressures are high. At present, it is suggested that superficial ulcers do not initiate as a result of pressure, but are more the consequence of shear and trauma to the tissue.[1] Prevalence of pressure ulcers in the spinal cord-injured (US veteran) population is reported to be as high as 39%.[2] This high prevalence indicates the need for prevention of PU development. To prevent PU development, the Agency for Healthcare Research and Quality (AHRQ, AHCPR guidelines 1994) recommends that wheelchair users shift their sitting posture at least once every hour. In addition, subjects who have sufficient upper-body motor function are advised to shift their posture every 15 min. However, two studies have measured the posture shift frequency of individuals that use a wheelchair for their mobility, and it was concluded that there is a wide variety in pressure relief intervals between subjects and that sitting times exceed the AHRQ guidelines.[3,4]

As individuals with spinal cord injury lack the sensory ability to register the need to reposition and the motor function to reposition, they are often dependent on nursing staff to reposition them. This is a time-consuming and cost-ineffective activity. Therefore, to reduce demands on nursing staff and increase the patient autonomy, seating devices have been developed that create dynamic, alternating seating patterns that mimic the reposition behavior as recommended by AHRQ. Both a dynamic cushion[5] and a dynamic seating device[6] have been studied as mechanisms to reduce tissue load. Positive effects of seating patterns with alternating loads were found on the skin oxygen tension of the buttock tissue. No conclusive results were found regarding the optimal actuation frequencies of dynamic seating patterns under consideration.

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Received 25 March 2009; revised 21 August 2009; accepted 10 September 2009; published online 27 October 2009

It is known that subjects without restrictions in sensory and motor functions do not develop PU, even if they sit for prolonged periods. Owing to a continuous variation in the sitting posture, and consequently the sitting load, they maintain tissue viability and as such do not develop PU. Recently some data regarding the sitting behavior of healthy subjects have become available, which can be helpful in defining optimal dynamic seating patterns. Linder-Ganz *et al.*[7] and Reenalda *et al.*[8] have investigated the sitting behavior of healthy subjects by measuring their posture shifts. Linder-Ganz *et al.*[7] found that healthy subjects change their posture approximately every 9 min in the sagital plane and approximately every 6 min in the frontal plane, as measured using pressure sensors and trunk movement analysis. Reenalda *et al.*[8] observed slightly higher values based on the measurement of interface pressure and subcutaneous tissue oxygenation, and concluded that healthy subjects change their posture at least every 8 min. This sitting behavior can serve as a basis for dynamic seating patterns with alternating loads.

The idea that individuals with a spinal cord disorder perform less posture shifts, and healthy individuals perform more posture shifts, than the AHRQ guidelines indicates the need for seating intervention. To impose dynamic sitting behavior on individuals with impaired sensory and motor functions, a fully adjustable, computer-aided (Matlab/Simulink environment) simulator chair (the Dynasit chair) was developed (see Figure 1). Previous studies have shown that the Dynasit chair is capable of controlling the body posture of sitting subjects,[9] regulating the sitting load[10,11] and elevating the subcutaneous tissue oxygenation below the ischial tuberosities.[12] However, these experiments with the Dynasit chair were only performed on healthy individuals. In this study, we focus on individuals suffering from a spinal cord disorder with impaired sensory and motor functions, which use a wheelchair for their mobility.

The objective of this study is to investigate the effect of dynamic sitting behavior on cutaneous and subcutaneous tissue oxygenations in individuals with spinal cord disorders. It is expected that the Dynasit chair is capable of imposing dynamic sitting behavior and increasing the tissue oxygenation.

Figure 1 The Dynasit chair, a computer-aided, adjustable simulator chair with parallelogram to control sitting posture.

Methods

Subjects

An explorative cross-sectional study was performed in ten male subjects with a spinal cord disorder (age: 58 ± 7.4 years; weight: 94.2 ± 16.6 kg, height: 1.82 ± 0.09 m). Subject characteristics can be found in Table 1. Subjects were all in the chronic phase of their spinal cord disorder and free of PUs for at least 2 years. Inspection of vascularization by medical staff revealed no abnormalities.

A dynamic sitting pattern was induced by means of the Dynasit chair. The study was approved by the local Medical and Ethical Committee. We certify that all applicable institutional and governmental regulations regarding the ethical use of human volunteers were followed during the course of this study.

Adjustable chair for postural actuation

Experiments were performed with the Dynasit chair that allows for sagital postural actuation and actuated pelvic rotation independently of the backrest and seat support. In addition, the chair contains a concept for actuated tuberal support. Seat and back angle are independently adjustable and by adjusting the configuration, the pelvis is actuated to rotate in the sagital plane without affecting the orientation of the trunk and thighs (see Figure 2). The fact that the pivot point of the seat is located right beneath the ischial tuberosities, and the pivot point of the backrest is located at the third lumbar vertebra, results in independent movement of the pelvis, which minimizes eventual shear forces during actuation.

Aligned to the seat pivot point and with an inter-tuberal distance of 120 mm,[13] two adjustable support elements were integrated in the seat plane (see Figure 3). The chair was equipped with a cushion, consisting of a wooden base plate with 100 mm of industrial foam as is commonly used in wheelchair cushions. Drill holes (∅ 90 mm) were made above the two adjustable support elements to allow for tuberal actuation. Actuators were covered with industrial foam.

Tissue oxygenation

Tissue oxygenation (SO_2 that reflects the oxygen saturation of hemoglobin) was measured using the Oxygen-to-See (O2C, LEA Medizintechnik Giessen, Germany). The O2C uses laser Doppler flowmetry and diffuse reflectance spectroscopy for noninvasive determination of oxygen supply in tissue perfused with blood. At present, O2C is the only device capable of noninvasively measuring the subcutaneous tissue oxygenation up to a measurement depth of 8 mm, reaching the muscle tissue. O2C transmits continuous wave laser light (830 nm and 30 mW) and white light (500–800 nm; 1-nm resolution; 20 W). The sample frequency of

Table 1 Subject characteristics

Subject	*Age (years)*	*Height (m)*	*Weight (kg)*	*Sex*	*Lesion level*	*Lesion type*	*AIS*
1	65	1.85	95	M	Th5	Incomplete	C
2	52	1.93	110	M	Th11	Complete	A
3	63	1.72	96	M	C5	Complete	A
4	55	1.76	76	M	*Paraplegia due to Strümpel's disease*		
5	53	1.78	82	M	Th10	Incomplete	C
6	52	1.88	100	M	Th9	Complete	A
7	56	1.78	75	M	Th12	Complete	A
8	66	1.77	67	M	C4	Incomplete	C
9	46	1.8	75	M	Th5	Complete	A
10	68	1.74	97	M	Th4	Incomplete	B

Abbreviation: AIS, ASIA impairment scale.
Nine subjects were diagnosed with a spinal cord injury, whereas one subject was diagnosed with spinal cord disease.

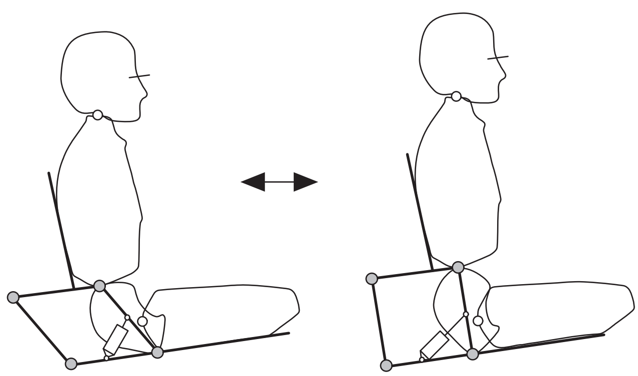

Figure 2 Concept for postural actuation and pelvic rotation in the sagital plane.

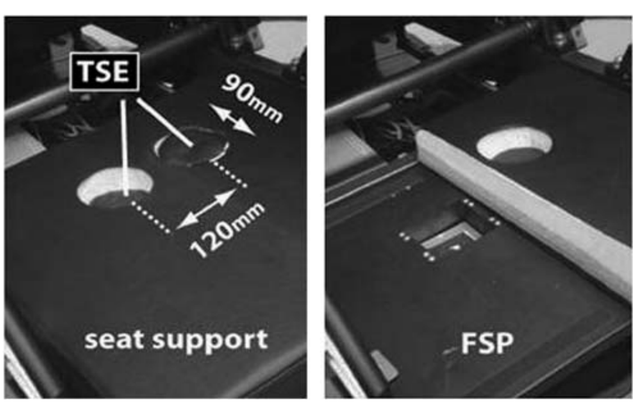

Figure 3 The left part of Figure 3 shows the cushion (seat support) of the Dynasit chair in which two round cutouts (∅ 90 mm) were made two allow for the actuation of the adjustable tuberal support elements (TSE). These tuberal support elements, constructed with an inter-tuberal distance of 120 mm, were covered with industrial foam. One TSE is lowered, the other is at level with the seat support. The right part of Figure 3 shows the base of the seat of the Dynasit chair (FSP; at the left), in which the adjustable tuberal support elements are integrated (TSE), and part of the cushion (at the right). Both TSEs are lowered.

the O2C is 0.5 Hz, which makes it suitable for measuring the dynamic response in blood flow in reaction to the changing seating load. Fiber-optic probes were custom-made to prevent interference with the seating interface. No confounding effects of the probes on the measurements are expected. The probes were attached to the skin with surgical tapes to prevent their displacement during the study.

Experimental setup and measurement procedures

Before and after the study, the skin of the buttocks of the subjects was inspected for tissue breakdown by a qualified and specialized nurse. An experimental protocol was developed in which the sitting load was altered every 5 min by actuation of the experimental chair. This frequency was obtained from a previous study in which healthy sitting behavior was analyzed, and a change in sitting posture was observed every 8 min.[8] However, 8-min sitting periods would result in extensive sitting time; therefore, 5-min sitting periods were chosen. Three types of actuation were imposed with the Dynasit chair in a non-randomized, non-controlled order: (A) change in sitting posture by adjusting the configuration of the seat and back of the chair; (B) static tubera actuation (STA) by means of the tuberal support elements; and (C) dynamic actuation of the pelvis (DA). The experimental protocol is displayed in Figure 4.

After an unloaded baseline measurement, the experiment was started with STA in SI10 (seat inclination of 10°). In these conditions, tuberal zones were loaded (L) and relieved (R) in alternating periods of 5 min. After STA, the effect of DA on tissue oxygenation was investigated. In the bilateral condition (DA, BL), actuation of both tuberal support elements in phase were performed with an actuation frequency of 1/30 Hz. In the contralateral condition (DA, CL), actuation of both tuberal support elements in contra-phase was performed with an actuation frequency of 1/30 Hz. In the dynamic pelvic adjustment condition (DA, P), the pelvis was actuated in the sagital plane by dynamically changing the configuration of the chair, as can be seen in Figure 1. In addition, sitting posture was changed to SI20 (seat inclination of 20°) after the DA, and the STA with loaded and relieved conditions was repeated. The total experimental protocol lasted for 39 min.

Data analysis

Given the repeated measures design and the low number of participants, nonparametric permutation tests for paired replicates were used to investigate the ability of the Dynasit chair to impose dynamic sitting behavior. The Wilcoxson signed-rank test for paired replicates was used to statistically compare the average values of different sitting conditions (A, B and C) with the baseline measurement and with the first loaded condition (STA SI10). In addition, this test was performed to statistically analyze differences within the groups (STA SI10 and SI20, and DA SI10). The significance interval was set at 95%. Owing to the explorative nature of this study, no correction for possible spurious significance levels was required.[14]

Results

Inspection of the skin of the subjects after completion of the experiment revealed no abnormalities.

All 10 subjects completed the experiment. However, tissue oxygenation data was incomplete for one subject (nr. 10) due

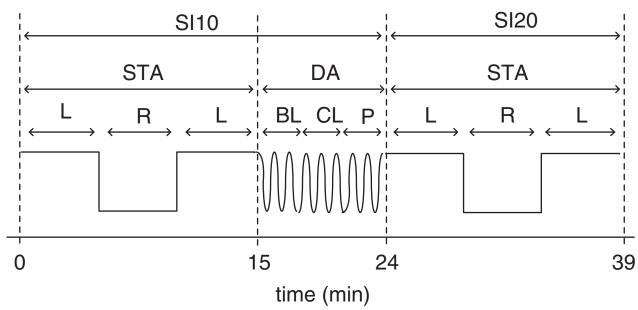

Figure 4 Experimental protocol (SI10, seat inclination 10°; SI20, seat inclination 20°; STA, static tuberal actuation; DA, dynamic actuation; L, loaded; R, relieved; BL, bilateral; CL, contralateral; P, pelvic). See text for further explanation of the experimental protocol.

to technical problems; therefore, analysis has been performed on the remaining nine subjects. Average values for (sub-)cutaneous oxygenation and their statistical significances relative to the baseline measurement and the different sitting conditions are given in Figure 5.

During the baseline measurement, cutaneous oxygenation was observed to be 52.3 ± 9.7%, whereas subcutaneous tissue oxygenation was 59.9 ± 11.3%. In the first loaded STA SI10 condition, minimum cutaneous SO_2 values of 22.2 ± 21.9 and subcutaneous SO_2 values of 40.0 ± 25.9% were observed. Maximal cutaneous SO_2 values of 63.4 ± 15.5 and subcutaneous SO_2 values of 55.0 ± 12.1% were observed in the relieved STA SI20 and relieved STA SI10 conditions, respectively. Maximal cutaneous SO_2 values differed statistically from the reference static sitting posture (STA SI10, L). Unloaded cutaneous and subcutaneous oxygenation values (SI10 R and SI20 R) did not differ significantly from the baseline values.

The increased tissue oxygenation value due to the actuation shows that there is a significant effect of actuation of the tuberal support elements on the subcutaneous tissue oxygenation ($P < 0.05$) in the SI10 sitting condition. Furthermore, dynamic tubera actuation (DA BL and DA CL) caused significant positive changes in cutaneous tissue oxygenation compared with the fully supported static condition. Dynamic tubera actuation (DA BL) showed significant positive effects on the subcutaneous tissue oxygenation.

Discussion

To prevent PUs, the dynamic sitting behavior of healthy subjects can be used as a reference value for seating devices

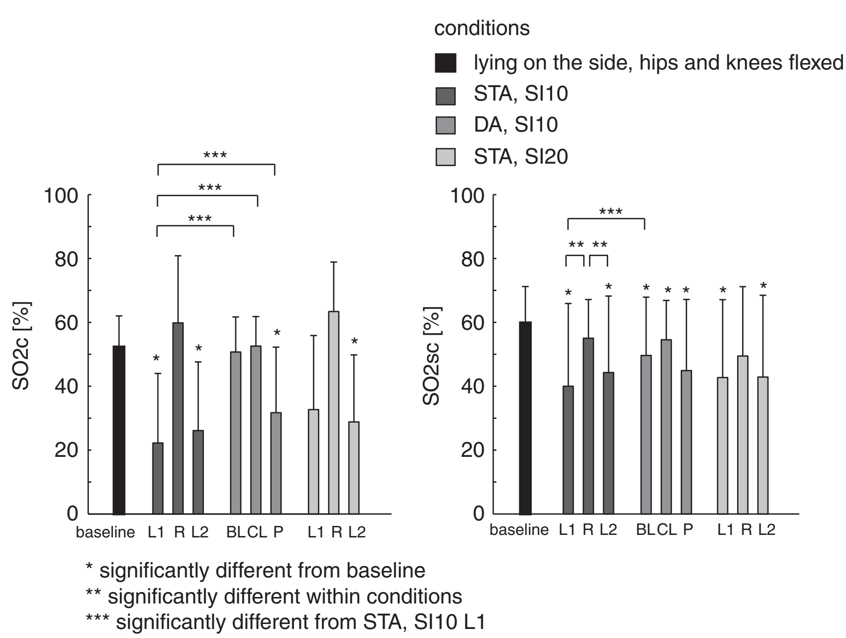

Figure 5 Average cutaneous SO_2 (oxygen saturation) (SO2c, left) and subcutaneous SO_2 (SO2sc, right) oxygenation and their statistical significance. (SI10, seat inclination 10°; SI20, seat inclination 20°; STA, static tuberal actuation; DA, dynamic actuation; L, loaded; R, relieved; BL, bilateral; CL, contralateral; P, pelvic).

that alternate the sitting load. This study investigated the effect of imposed dynamic sitting behavior, by means of the Dynasit chair, on cutaneous and subcutaneous tissue oxygenation in individuals with spinal cord disorders. It can be concluded that the Dynasit chair is effective in alternating the seating load in spinal cord-injured subjects, resulting in significantly elevated cutaneous and subcutaneous tissue oxygenation values compared with a reference static sitting posture. In this study, increases in SO_2 values of 41.3 (cutaneous) and 15% (subcutaneous) were observed as a result of actuation. Although the increase in SO_2 value, as a result of a single posture shift in healthy subjects is $2.2 \pm 2.4\%$,[8] it indicates the ability and potential of the Dynasit chair of increasing the tissue oxygenation and of reducing the chance of tissue degradation. Although oxygenation levels in the loaded sitting conditions (SI10 L1, L2 and SI20 L1, L2) were significantly lower than baseline, unloaded cutaneous and subcutaneous oxygenation values (SI10 R and SI20 R) did not differ significantly from the baseline values. During unloading of the ischial tuberosities, tissue oxygenation was as high as the unloaded baseline values. The Dynasit chair is, therefore, capable of imposing a dynamic sitting behavior that mimics the sitting behavior of healthy subjects as described in the literature.[7,8]

Previous studies have shown the positive effects of alternating sitting postures on the buttock load in healthy subjects and spinal cord-injured patients. Significant effects of different sitting postures on interface pressure were found,[15–17] and previous experiments using the Dynasit chair confirmed positive effects of postural variation on sitting load in healthy subjects.[10–12] Other studies have demonstrated the ability to change cutaneous tissue oxygenation by means of a dynamic cushion[5] and by means of a wheelchair in which the back part of the seat could be lowered to relieve the ischial tuberosities.[6] This study confirmed the ability of a seating device to create an alternating load on the seating surface of individuals with spinal cord disorders and, unlike the aforementioned studies, based its experimental protocol on the sitting behavior of healthy subjects.[8]

Similar to previous studies, this study used the noninvasive measurement of cutaneous oxygenation. In addition, it noninvasively measured the subcutaneous tissue oxygenation using the O2C. The O2C is, at present, the only device that is capable of noninvasively measuring the oxygenation of the subcutaneous tissue up to a maximum depth of approximately 8 mm. Previously used techniques to quantify tissue perfusion or oxygenation do not possess penetration depths sufficient to reach the muscle tissue and, therefore, are restricted to measure the perfusion and oxygen saturation of the skin and sub-cutis only.[18–19] However, owing to its high metabolic demand, muscle tissue is most sensitive for developing pressure ulcers.[20] During sitting the muscle gluteus maximus is located at approximately 7–15 mm deep, depending on the anatomy and geometry of other tissue structures. This means that in this study, a part of the signal from the subcutaneous measurement indeed originated from the muscle gluteus maximus, and a part of the signal originated from other subcutaneous structures.

This study demonstrated higher cutaneous and subcutaneous tissue oxygenation values as a result of dynamic sitting. Tissue oxygenation is an important factor in the development of deep tissue injury especially. It is plausible that the elevation of the tissue oxygenation to a level comparable with the unloaded baseline values indicates a reduced change of tissue degradation during long-term sitting. However, more factors have a function in the development of PUs and deep tissue injury. Friction and shear are associated with the development of superficial PUs.[21,22] Deformation of the tissue is an important factor in the development of deep tissue injury.[23,24] Individual factors that influence the ability of the tissue to withstand load, such as level of mobility, atrophy and vascularization, also have a function. On the basis of the assumption that higher oxygenation leads to a reduced chance of tissue degradation, and accounting for the factors mentioned earlier, it is plausible to state that individuals with spinal cord disorders should be able to sit for longer periods of time without tissue breakdown if dynamic sitting behavior is imposed compared with static sitting.

Given the repeated measures design and the low number of participants ($n = 9$), multiple nonparametric tests were performed to statistically compare different sitting conditions. Performing multiples tests usually increases the risk of a type-I error. However, our study was explorative in nature. The data were collected with a clearly defined objective, but not with a pre-specified key hypothesis. Therefore, multiple test adjustments were not strictly required. To confirm the results of this study, corresponding hypotheses have to be tested in further confirmatory studies with higher numbers of participants and a randomized protocol.

It can be concluded that the developed system for actuated dynamic sitting support is effective in alternating the seating load in individuals with a spinal cord disorder. The imposed dynamic seating pattern that alternates the load on the sitting surface (by means of static and dynamic actuation of the tuberal support elements), resulted in significantly elevated cutaneous and subcutaneous tissue oxygenation levels compared with the reference static sitting posture. Consequently, the Dynasit chair is capable of imposing dynamic sitting behavior in individuals with a spinal cord disorder, and thereby reducing the chance of tissue degradation compared with static sitting. This reduced chance of tissue degradation should enable individuals that use a wheelchair for their mobility to sit for prolonged periods of time without tissue breakdown. At present, the Dynasit chair is an experimental seating device intended for research purposes. However, conceptual parts of the Dynasit chair, such as the concept for tuberal actuation, can be integrated into standard wheelchairs.

Acknowledgements

We thank the engineering company Demcon (Oldenzaal, the Netherlands) for developing the experimental simulator chair; Karin Groothuis, PhD, for her assistance with the statistical analysis; Birgit Molier, MSc, for assisting during the experiments and the nursing staff of the outpatient department of het Roessingh Centre for Rehabilitation (Alice Plegt, Joke Broeze, Desiree Barkel and Rolien Brink) for their assistance during the experiments. This study was funded, in part, by the Dutch Ministry of Economic Affairs, SenterNovem (TSIT3043).

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