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RELATIONSHIP BETWEEN BODY-SEAT INTERFACE PRESSURE AND DISCOMFORT DURING ROWING

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Abstract

Discomfort and pressure-related tissue injury to the buttocks are common complaints among rowers. The soft tissues of the buttocks are non-uniformly loaded during rowing. The current state of literature on seating discomfort is inconclusive as to a desirable body-seat interface pressure pattern. The purpose of this study was to determine whether localising pressure under bony protuberances or diffusing pressure over soft tissues would result in the least amount of discomfort. Force sensing arrays were used to measure body-seat interface pressures in 11 elite female rowers during rowing. Peak pressure measures were identified and pressure gradients were calculated. Discomfort was quantified using a questionnaire, and pressure data were then correlated with discomfort scores. Discomfort was weakly correlated with each of maximal pressure gradient (r=0.45) and peak pressure (r=0.43). The findings indicate pressure should be redistributed in order to avoid concentrating pressure under the bony protuberances of the buttocks.

Keywords

Pressure mapping, FSA, Force sensing array, rowing, seat, sport equipment.

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Further, this project could not have been completed without the support from Hudson Boatworks (London, Ontario). Your provision of a variety of rowing seats allowed us to operationally achieve the goals of this study.

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Additionally, I gratefully thank Al Morrow and the National Canadian Women's Rowing team for their enthusiasmduring this project. Without their participation, the strength of this study would be reduced. Further, they have allowed us to shed light on the examination of women's athletic equipment that has received little attention.

I would also like to thank Dr. Jan Polgar for offering her expertise in body-seat pressure mapping during the design stages of this project.Her input allowed us to properly evaluate equipment candidates.

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List of Abbreviations

Phrase	Abbreviation
XSensor LX200 pressure sensing array	XSensor mat
Tekscan 6900 sensor, with Evolution ™ handle	Tekscan sensor
Tool for Assessing Wheelchair discomfort	TAWC
General Discomfort Assessment	GDA
Interface pressure	IP
Ischial tuberosity	IT
Isokinetic Rowing Ergometer	ergometer
Sensel of interest	SOI
Coefficient of variation	CV
3M Micropore™ surgical tape	tape

1. Introduction

Pressure-related tissue injuries and discomfort to the buttocks, particularly in female rowers, during rowing have been reported (Nolte, V., Personal communication, August 24, 2009; National Canadian Women's Rowing Team members, Personal communication, June 29, 2009). A source of such discomfort is the contact area between the rowing seat and the superior-posterior thigh and buttocks. Currently, there is no peer reviewed literature regarding body-seat interface pressures in rowing. Wheelchair studies indicate that injury can arise from the a seating surface as a result of pressure applied to the skin, shear across the seat, and internal shear amongst the inferior protuberances of the pelvis and coccyx, and the surrounding soft tissues (Bennett & Lee, 1986).

The original patent for the sliding rowing seat dates back to 1870. At the time, rowing was a predominantly male sport. The original seat design was created for men, and rowing seats have not been modified greatly since. Conventional rowing seat design incorporates two holes intended to accommodate the ischialtuberosities (IT), and a cut-away section to accommodate the coccyx (Figure 1). However, few sizes are commercially available and rowing seats are generally not custom made. As a result, the placement of the ITs relative to the seat holes is often not ideal for an individual rower's anatomy.

Additionally, the pressure-related injuries self-reported by the aforementioned rowers include both superficial injuries (abrasion, blisters), and deep injuries (bruising, bony deformation). These problems are compounded in female rowers due to unsuitable placement of the seat holes for the female anatomy. The aforementioned complaintscall the needs of modern rowing seat design into question.

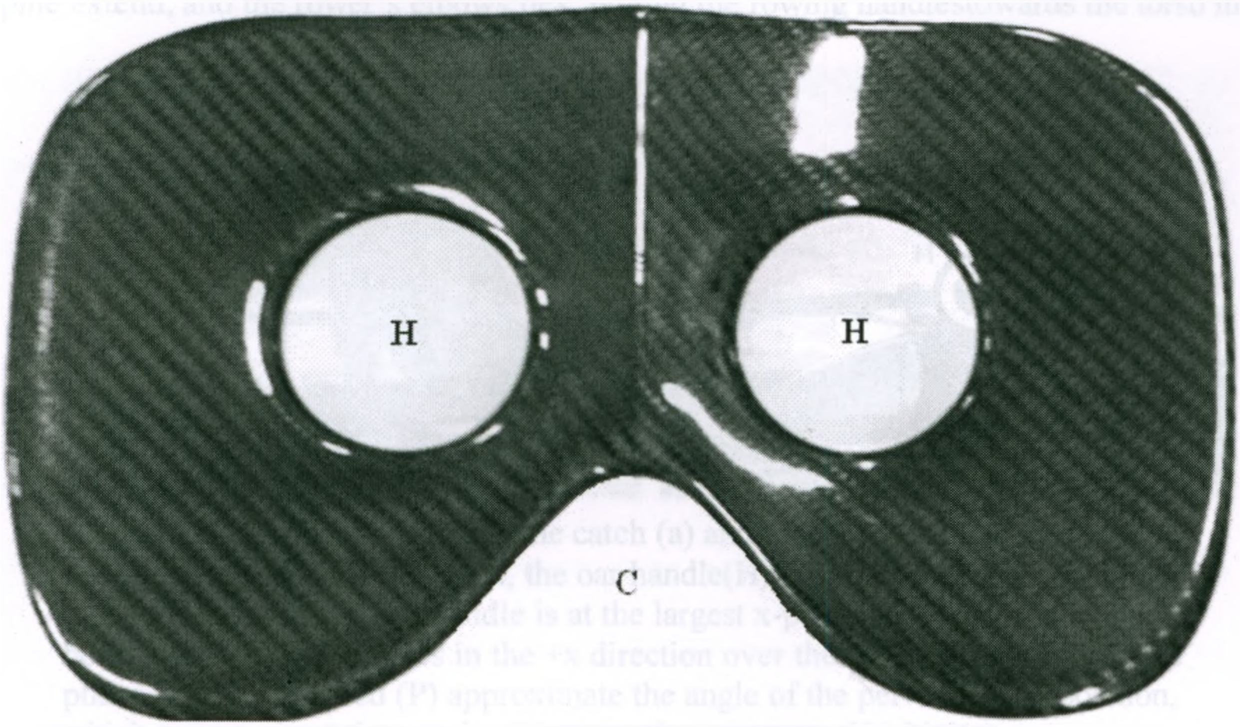

Figure 1 Rowing seat with (H) seat holes intended to accommodate the ITs and (C) cut-away section intended to accommodate the coccyx.

Rowing is a dynamic occupation that occurs in a seated position. The rowing stroke can be described in terms of two positions; the *catch* (Figure 2a) and the *finish* (Figure 2b). In the coordinate system described in Figure 2, the rower is facing the negative-x direction. The catch is a position where the rower's knees and hips are flexed and the wrists areextended with the rowing handle to the smallest x-position. The finish is a position where the rower's hips and knees are extended and the wrists are at the greatest x-position.

The propulsive part of the stroke termed the *drive* begins immediately following the catch position and ends at the finish position. During the drive, the knees, hips, and lumbar spine extend, and the rower's elbows flex, pulling the rowing handlestowards the torso in

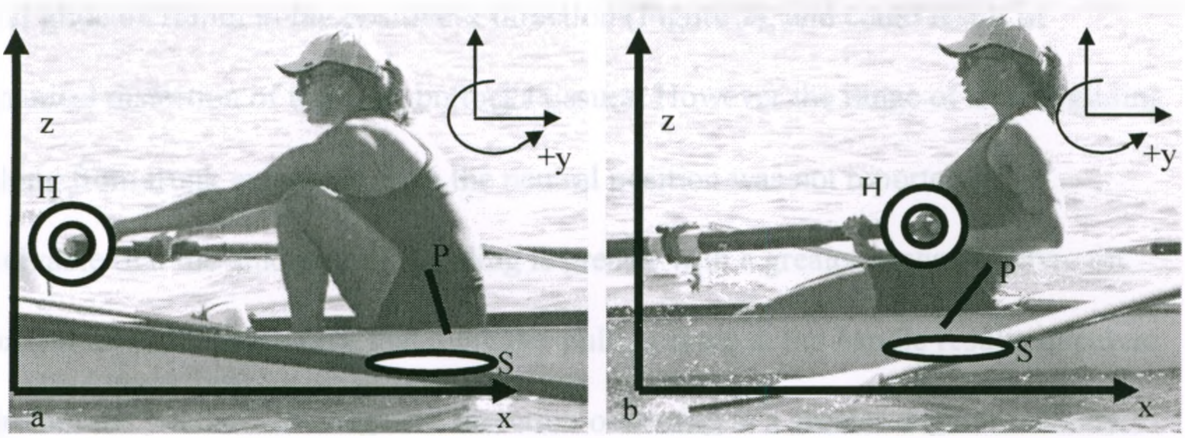

Figure 2 Photographs showing the catch (a) and finish (b) position in a global coordinate system. At the catch, the oar handle(H) is at the smallest x-position, while at the finish the oar handle is at the largest x-position. The rower's upper body center of mass moves in the +x direction over the seat (S) during the drive phase.Thelines marked (P) approximate the angle of the pelvis at each position, which rotates about the y-axis. (Photographs courtesy of V. Nolte)

the positive-x direction(McGregor et al., 2002). The rower's upper body mass moves in the positive-x direction over the seat. The return from the finish to the catch position is the non-propulsive part of the rowing stroke termed the *recovery*. During the recovery, the knees, hips, and lumbar spine flex, and the rower's upper body mass shifts in the negative-x direction over the seat. Pollock et al. (2009) note that pelvic, spinal, and extensor muscle activation timings were similar (nearly simultaneous firing) during the drive, as were the flexor patterns during the recovery.

During the drive phase, hip extension is concomitant to pelvic tilt around the y-axis in the negative direction, and hip flexion is concomitant to pelvic tilt in the positive direction during the recovery phase (McGregor et al, 2002; Pollock et al., 2009). In elite female rowers, a range of 40.9° has been reported during rowing (Pollock et al., 2009). The pelvic rotation during rowing causes the ITsto glide in the sagittal planeover the seat surface. The range of ischial gliding in rowing has not been reported. Hobson and Tooms (1992) report that trunk flexion of 30° from neutral in wheelchair sitting will result in an ischial glide of 16mm in the positive-x direction (Figure 2), and could result in mechanical distortion of the deep buttocks tissues. However the range of ischial gliding resulting from trunk extension from the neutral position was not reported. It is conceivable that the amount of IT gliding is greater with a greater range of pelvic tilt. Pollock at al. (2009) also note that a greater pulling force at the handle results in pelvic tilt around the y-axis in the negative direction occurring at a greater angular velocity. The pelvis exhibits an angular acceleration in the sagittal plane during the period of peak force production at the handle during the drive, indicating that the pulling force required at the oar handle is partly produced at, and transmitted through, the hip (Pollock et al., 2009). Trunk movement in well-trained rowers can range from 30° flexion at the catch to 28° extension at the finish measured relative to the y-axis (Hosea et al., 1989).These studies indicate that the interaction between the rowing seat and the buttocks is dynamic. As the rower's pelvis rotates about the hip, the bony protuberances of the pelvis move in the sagittal plane with respect to the seat surface.

2. Literature review

There is a no peer reviewed literature regarding body-seat IP in rowing available. However body-seat IP mapping has been used extensively in wheelchair studies. It has been found that movements while seated can generate high transient pressures between the body and seat in wheelchair studies (Bardsley, 1977; Davies, 1978). High pressures cause mechanical distortion of soft tissues and localized ischemia, which can lead to pressure ulcers and irreversible pressure damage to both soft and hard tissues (Tam et al., 2003). It is important to distinguish between different types of pressure-related tissue injuries; superficial injuries such as blistersand deep injuries such as muscle damage and bony deformations. Superficial pressure injury occurs from pressure and shear stressexperienced by the skin, whereas deep pressure injury results from sustained internal loading that penetrates through to deep tissues (Sanders et al.,1995). Blisters, muscle damage, and deformations of the buttocks are all injuries reported by the National Team and UWO Head Rowing Coach ((Nolte, V., Personal communication, August 24, 2009; National Canadian Women's Rowing Team members, Personal communication, June 29, 2009).

The etiology of pressure injury is multifactorial. Pressure, tissue loading, tissue deformation (Dinsdale, 1974;Neumark 1981), shear stress (Bennett et al., 1979), tissue tolerance (Kamijo, 1982),temperature and moisture (Hyman and Artigue, 1972; Trandel and Lewis, 1975), and the seat characteristics all contribute to pressure-related tissue injury (Husain, 1953; Chung, 1987).Most of these factors are modifiable by changing the rowing seat.

In addition, the viability of soft tissues is dependent upon tissue oxygenation (Mathieu & Mani, 2007; Tam et al., 2003), including proper microcirculation of bloodin the skin and subcutaneous tissue (Mathieu & Mani, 2007). Excessive or prolonged application of mechanical forces may cause vascular occlusion and ischemia (Kosiak, 1961; Brand, 1976). It has been found in non-rowing studies that while seated, the blood supply to the soft tissues beneath the ITs is inversely related to the contact load(Koopman et al., 2010). High pressures to the buttocks during rowing training can be prolonged over several hours and are likely to be sufficient to cause localized ischemia in the skin and subcutaneous tissues of the buttocks. This suggests that dispersing body-seat IP in order to minimise externally applied pressures would be appropriate.

It is difficult to identify a specific threshold of stress needed to cause pressure injury or discomfort to the buttocks, as the existing literature is mixed with regards to pressures reported, the skeletal and soft tissues (and thus pressure tolerances) examined, and the conditions under which load is applied. The mean maximal IP value associated with normal sitting on a hard surface in a wheelchair in healthy females is $10.2N/cm^2$, however mean sitting pressures are as low as $2.8N/cm^2$(Thorfinn et al., 2002). Further, the pressure under the buttocks described as comfortable was only $0.58N/cm^2$ (Kamijo, 1982). The pressure values associated with pressure injury to the buttocksin wheelchair studies range from 0.4 – $10.67N/cm^2$ (Bennett and Lee, 1986). Further, externally applied pressures ranging between 0.8-$1.73N/cm^2$ have been reported to be sufficient to completely occlude local vasculature to sacral tissues (Bader, 1990). It appears that the body-seat IPs seen during normal sitting can be sufficient to cause pressure injury to the buttocks if applied for extended periods of time.

Theinterface contact area between the body and the rowing seat is less than 600N. In research examining smaller body-surface contact areas, such as amputee sockets, skin and subcutaneous tissue breakdown from pressure and shear is a paramount concern (Sanders et al., 1995; Zhang et al., 1998). Body-prosthesis IP as low as $0.93N/cm^2$ has been shown to produce ischemic skin conditions conducive to pressure injury development (Sangeorzan et al., 1989). Further, research examining diabetic subjectswho are predisposed topressure-related tissue injury suggests a critical pressure of $110N/cm^2$

for foot pressure injury (Lavery et al, 1997). However, these studiesaddress body parts that have different load tolerances than the buttocks, and cannot provide a criterion IP for discomfort or injury for this study.

The fashion in which pressure is applied is also a concern for the development of pressure injuries. Some literature reports skin damage to require pressure application for long durations (Kosiak, 1961; Brand, 1976). Pressure is applied to the buttocks in a cyclical fashion during rowing; however,blisters on the buttocks were a common complaint from female rowers (Canadian National Rowing Team, Personal communication, June 29 2009). Additionally, the application of high external pressure over 4 hours has been shown to be sufficient to cause muscle damage in swine (Daniel et al., 1981). Further, the dynamic tissue loading during gliding of the bony protuberances may cause mechanical abrasion of the skin, contributing to pressure-related tissue injury (Sanders et al., 1995). Given these findings and the reports of pressure-related soft tissue injury from rowers, it seems that constant pressure application over a long duration is not requisite to either superficial or deep soft tissue damage. The nature of pressure application to the buttocks during rowing appears to be conducivepressure injury.

Factors in the etiology of superficial pressure injury include mechanical distortion and shear stress in the skin. Blisters result from the separation of dermal layers due to friction and shear experienced by the skin. In order for friction to exist at the body-seat interface, pressure must exist at the interface. The application of external pressure will almost certainly produce a shear stress in soft tissues, and the production of shear stress is almost always accompanied by pressure application (Bennett & Lee, 1986). Normally applied pressure to the buttocks, localized pressure, a non-uniform pressure distribution (such as that produced by a rowing seat), or pressure causing tissue distortion alone, will all involve shear (Chow & Odell, 1978). Shear stresses can thus be induced by normal forces applied to the buttocks. According to Bennett and Lee (1986), internal shear stresses are proportional to the interface pressure gradient between the body and an external surface. Further, the amount of pressure needed for tissue ischemia is nearly halved when adjunct to adequate shear, as the combination of pressure and shear particularly promotes vascular occlusion (Bennett & Lee, 1986).

Body-seat IP distribution is an objective measure that iswell associatedwith discomfort (de Looze et al., 2003);however, there is an inconsistency in the literature with regards to how pressure should be distributed in order to avoid discomfort and injury.

On one hand, Bennett and Lee (1986) emphasise that the application of a localized pressure generates relatively large shear stresses, where a more uniform application of pressure does not. Thus, as the pressure gradient increases in magnitude (such as localised pressure under a bony protuberance), the resultant internal shear stress increases and poses a greater likelihood of pressure injury and discomfort.

Alternatively, research examining the body-seat interface found that a larger and more uniform body-seat contact area (such as sitting on a stability ball as compared with a small wooden stool), resulted in increased levels of discomfort (Gregory et al., 2006). A uniform pressure distribution entails a transfer of a portion of the high stresses under the ischialtuberosities, which have a higher pressure threshold, to the soft tissue of the gluteal region, presumably increasing soft tissue deformation (de Looze et al., 2003; Gregory et al., 2006). Non-rowing seats that have been described as "comfortable" presented a mean pressure level of 0.3N/cm^{2}under the gluteal region, which is half the comfortable mean pressure under the ischialtuberosities of 0.58N/cm^2 (Kamijo, 1982). These findings demonstrate that discomfort may arise more easily if pressure is dispersedamong the soft tissues of the buttocks, and that low pressures are capable of causing discomfort to the buttocks in multiple areas.Additionally, bicycle studies concerned with saddle pressure redistribution state that pressure should be redistributed away from the soft tissues of the perineum and localised to the ITs, as the perineum has a relatively poor load tolerance (Spears et al., 2003; Lowe et al., 2004). These reports suggest that we should consider redesigning the rowing seat to concentrate pressure under the ITs.

The research regarding the redistribution of seat pressure is inconclusive as to whether pressure redistribution away from the bony tissues or dispersion amongst the soft tissues is desirable in order to reduce discomfort and the risk of injury. The present investigation included a varying degree of body-seat IP dispersion in order to address both conceptual frameworks. The design of the rowing seat influencesthe degree of IP dispersion, tissue deformation, and internal shear stress in the buttocks.Thus, the body-seat IP magnitudes and distribution are important to study as they are modifiable by altering the rowing seat.

3. Goal, purpose, and hypotheses

The goal of this study was to determine the desirable and undesirable shape characteristics of rowing seats as they pertain to discomfort. This information may be useful in designing a novel and more comfortable rowing seat. It could be reasoned that improved comfort while rowing may lead to performance increases.

The purpose of this study was to determine whether localising pressure under bony tissues or diffusing pressure will result in the least amount of discomfort. This study aimed to pinpoint regions of discomfort and high IP across a number of rowing seats, and then quantify the peak pressures and the degree of pressure localisation. Pressure data and discomfort questionnaire scores were correlated to quantify the relationship between the degree of pressure localisation and discomfort.

It was hypothesized that:

1. Increased pressure dispersion, and thus conceivably less internal shear stress, will result in less discomfort.
2. Lower measured peak IPwill result in less discomfort.

4. Methods

4.1 Sampling

This study concerns the possible improvement of rowing seats. The participants were skilled and consistent rowers in order to ensure that the pressure measurements were representative of the pressures experienced by an athlete executing proper rowing form. Participants were recruited from the National Canadian Women's Rowing Team(Table 1). Female rowers were recruited exclusively as modern rowing seat are variations of adesign over 150 years old that was originally designed for male rowers. Conceivably, discomfort is experienced more often by female rowers, and addressing sex-specific seat design issues is important. Inclusion criteria for the participants were the following: Participants must be elite rowers, in good health, and be deemed fit to perform rowing ergometer exercise for prolonged periods of time while producing a consistent rowing form. Exclusion criteria for the participants were the following: Subjects must not have any pressure-related injuries to the buttocks or upper thigh at the start of the trial period. Subjects must not have any condition limiting key movements; including anterior and posterior pelvic tilt, and hip, spine, knee, and ankle flexion and extension.

Table 1 Participant age and mass.

Participant number	Age	Mass (kg)
1	36	63
2	35	62
3	33	73
4	26	74
5	31	80
6	28	78
7	28	70
8	31	74
9	28	76
10	32	76
11	29	75

A-priori calculations used to determine the sample size returned n = 11 (Soper, 2011). These calculations were in preparation to calculate correlations between pressure measures and discomfort using the following parameters,; α-level = 0.05; desired statistical power = 0.8; Coefficient of determination = 0.5.

4.2 Equipment and strategy

This study involved the use of the following equipment and materials:

a. Isokinetic indoor rowing ergometer (Figure 3& 4)
b. Six rowing seats (Figures 5-10)
c. XSensor LX 200 pressure sensing mat (XSensor mat) with laptop computer and X3 Pro software (Figure 11)
d. Tekscan 6900 (Tekscan sensor) pressure sensor with Evolution handle, and laptop computer with I-Scan software (Figures12 & 13)
e. 5cm wide 3M Micropore™ tape (model # 1530-2)
f. Discomfort survey (Appendix A)

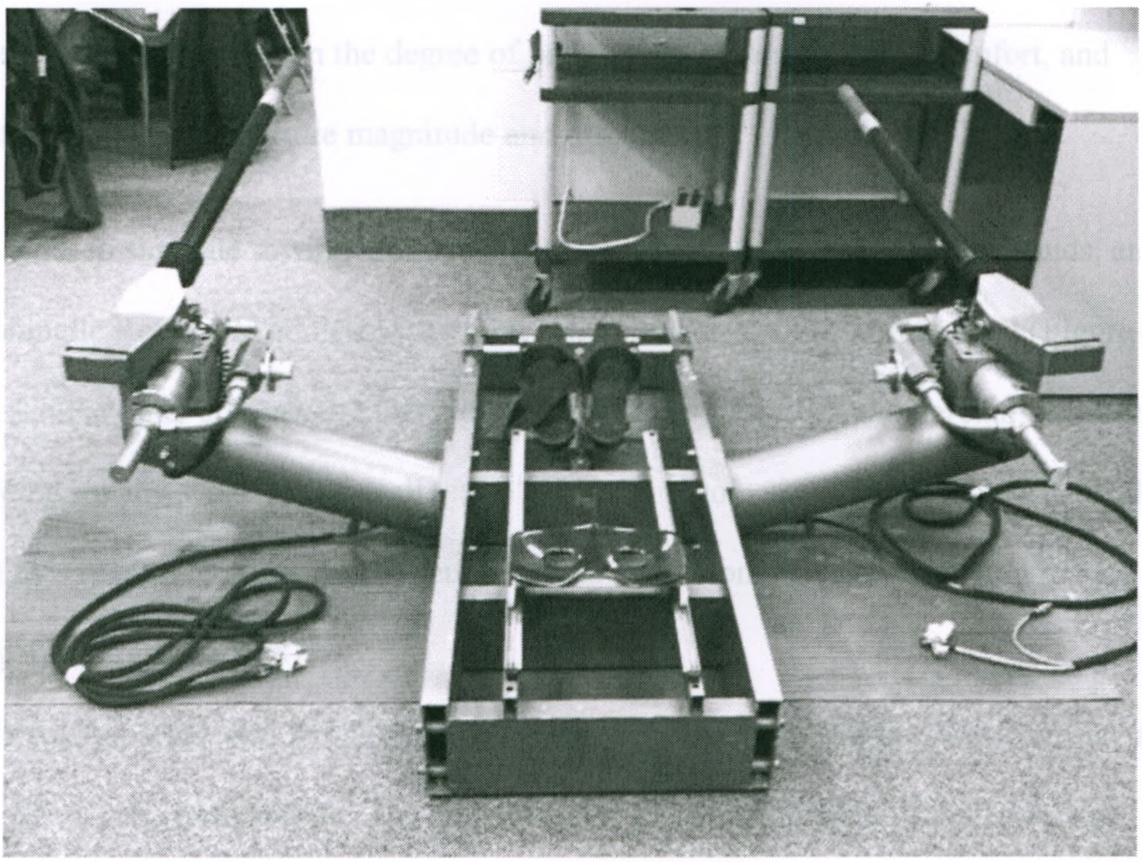

Figure 3 Posterior, view of the Isokinetic Rowing Ergometer.

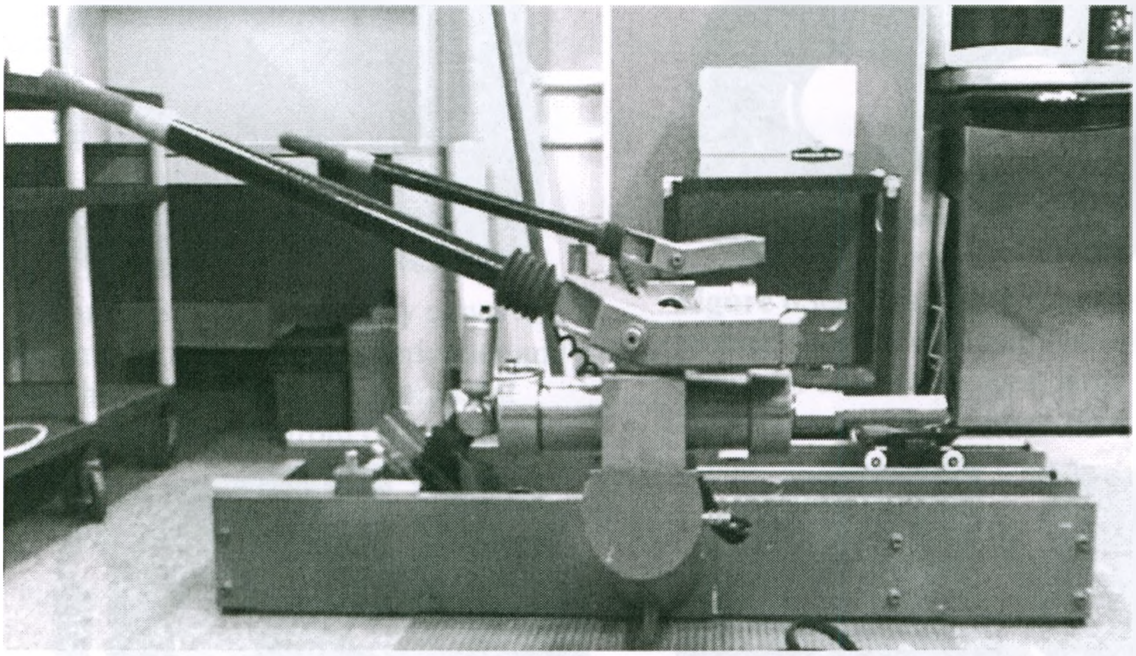

Figure 4 Side view of the Isokinetic Rowing Ergometer

The novel nature of this study necessitated a multi-stage approach. This study concerned the relationships between the degree of pressure localisation and discomfort, and between the peak pressure magnitude and discomfort.

In order to simulate rowing indoors, and to control for environmental confounds, an Isokinetic Rowing Ergometer (hereafter referred to as ergometer) was used (Figure 3& 4). Unlike other ergometers, this ergometer permits the use of commercially available sliding rowing seats. Additionally, this particular ergometer's design biomechanically mimics rowing on water more accurately than other commercially available rowing ergometers (Nolte, 1987).

The rowing seats used in this study vary in material and topography; however they are all variations of a basic design. The six seats used are all commercially available, and include four carbon fibre seats (Figures 5-8), one plastic (Figure 9), and one wooden seat (Figure 10).

Figure 5 Seat 1 has a highly concave seating surface, bevelled perimeter and seat hole edges,withoutunboredseat holes, and is made from carbon fibre.

Figure 6 Seat 2 is highly concave buttock support, minimally bevelled perimeter and holes edges, large diameter seat holes, carbon fibre.

Figure 7 Seat 3 is constructed from carbon fibre, has a highly concave buttocks support, bored holes, and sharp edges around the perimeter of the seat and holes.

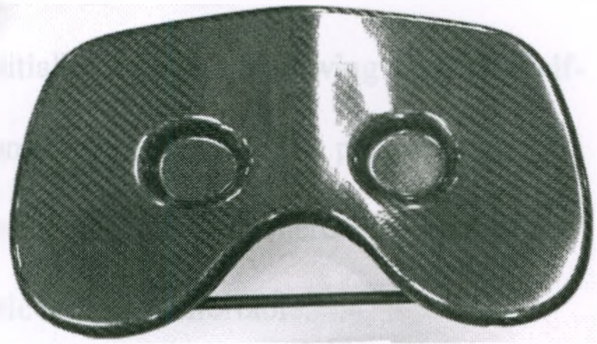

Figure 8 Seat 4 is carbon fibre, has a relatively flat buttocks support, non-bored holes, and bevelled edges.

Figure 9 Seat 5 is constructed from plastic, with a relatively rough surface. The seat holes are not bored and are irregularly shaped. It has relatively flat buttocks support, and bevelled edges along the holes. The outer perimeter is both bevelled and sharp.

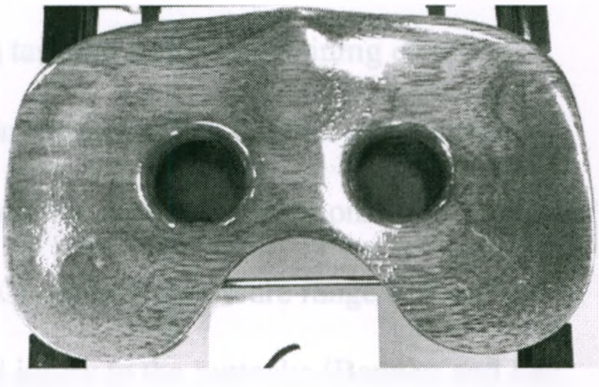

Figure 10 Seat 6 is constructed from wood, with a smooth surface. The seat holes are bored and circular. It has relatively extreme concavity towards the perimeter. The holes edges are slightly bevelled, whereas the outer perimeter is a sharp crest.

In order to study the relationship between the amount of applied pressure and discomfort, and between IP gradients and discomfort, varying peak IPs and varying degrees of pressure dispersion were required.This was operationally achieved by using multiple participants and an array of seats varied in shape.

Four pre-tests were initially carried out to determine the following parameters; pressure range, pressure variability, frequency characteristics, and sensor spatial resolution.

During the actual test trials, the participants initially tested all six rowing seats and self-reported the most comfortable, and the most uncomfortable seat. The present study employed a within-subjects repeated measures research design, where each participant tested the two seats self-reported as comfortable and uncomfortable.

The degree of IP dispersion was quantified by measuring the IP distribution across the seat, and calculating spatial pressure gradients in all directions. Body-seat IP mapping is a previously validated measure of interface pressure between the clothing and seat, and is reliable during both static sitting and reaching tasks in a study examining center of pressure (Lacoste et al., 2006). Further, pressure mapping has produced repeatable, objective measures in normal sitting and automotive seating applications (Kolich&Taboun, 2004; Stinson et al., 2003).Given that a pressure range of from 0.4 – 10.67N/cm^{2}is associated with pressure-related injury to the buttocks (Bennett and Lee, 1986), a high pressure criterion value of 10.67N/cm^2 was used in this study.

Two force sensing arrays were used in this study to measure pressures at the body-seat interface. An XSensor mat (Figure 11) was used early in the test protocol to image the pressure distribution across the rowing seats, and locate areas of high IP. The

XSensormat has a sensing area of 2090cm^2, sufficient to completely cover the approximately 600cm^2 surface area of the seats. The spatial resolution of the mat is 1.27cm in both dimensions. The XSensor mat was pre-calibrated by the manufacturer to detect pressures from 0.07-10.34 N/cm^2, with an accuracy of ± 0.82% full scale output per sensing point.

Figure 11XSensor system including pressure sensing mat, analog to digital converter, power supply, and PC. Adapted from XSensor Technology, 2011.

The present study concerns the spatial distribution of body-seat IP. Calculating mean pressures across a seating surface where IP is unevenly distributed would not provide much meaningful information (Sprigle et al., 2003). Much of the rowers' upper body weight is concentrated within an area less than 600cm^2; less than that of most desk chairs. Pressure will concentrate on crest and edges that protrude into the buttocks. As a result, the IP values were expected to exceed that of normal sitting and exceed the pressure sensing range of the XSensor mat;the spatial changes in pressure were expected to be drastic. In light of this, it was determined that IP gradients must be calculated over small distances in order to avoid underestimating gradients. While the peak pressures at the body-seat interface exceeded the upper sensing limit of the XSensor mat, it was capable of localizing regions of high pressure. In order to measure pressures greater than 10.34 N/cm^2in these regions, a higher spatial-resolution Tekscan sensor was used (Figure 12&13).

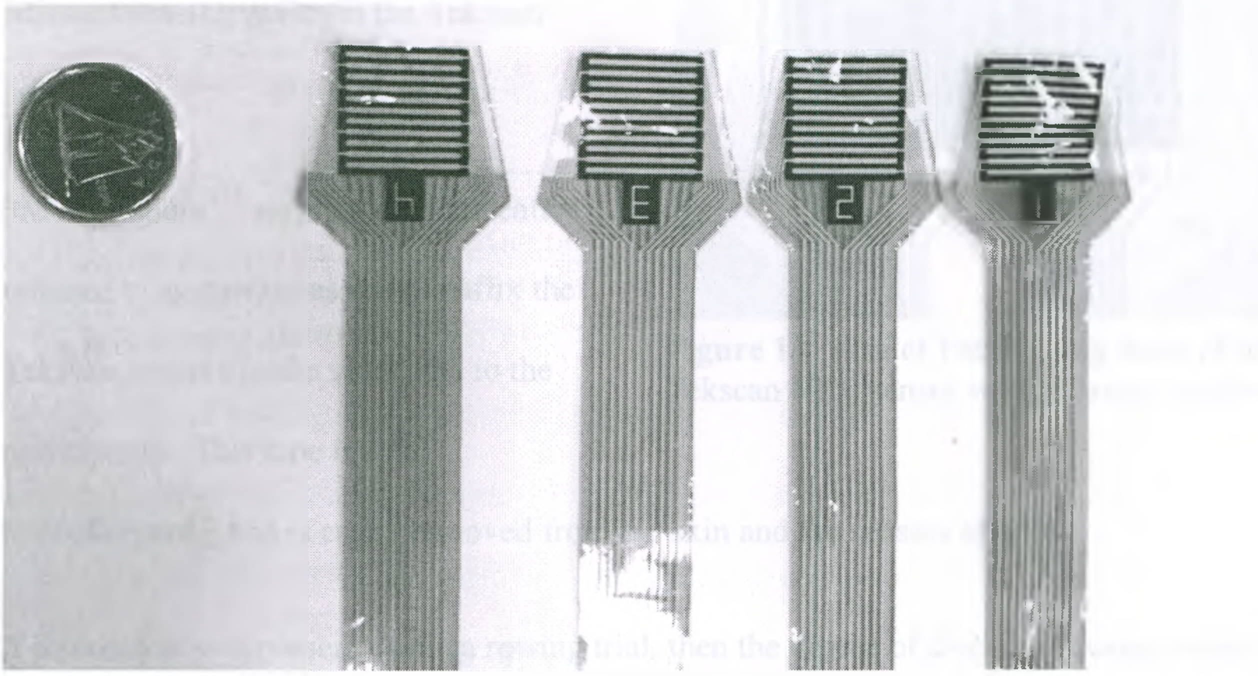

Figure 12 Tekscan 6900 sensor, showing four sensing areas. Size comparison made using a dime.

The Tekscansensor contains four sensing areas that can be placed in different areas of the body-seat interface. Each of the four sensing areas is of the dimensions13.97mmx13.97mm, and is 0.1mm thick(Figure 13). Each sensing area contains an 11x11 matrix of sensing points (121 points in total) with a spatial resolution of 1.27mmin both dimensions.

The Tekscan sensor utilizes pressure sensitive ink to detect applied pressures, and is capable of measuring pressures up to 6895 N/cm^2. The consistency of measurements using the Tekscan sensor was tested during the pre-tests in this study. IP gradients were later calculated between adjacent sensing points in the Tekscan sensor.

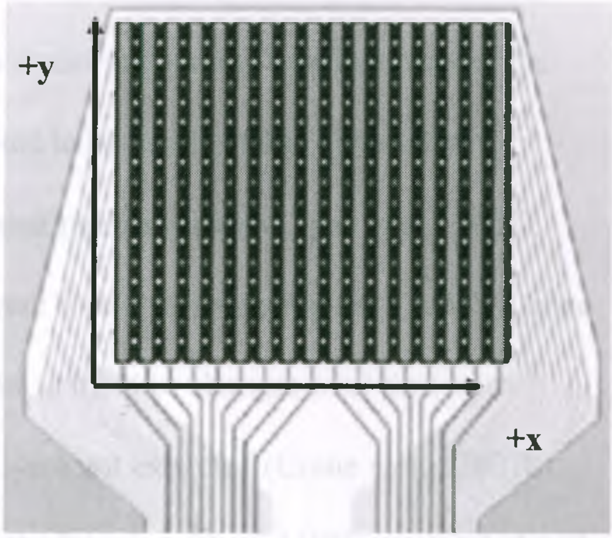

Figure 13 One of four sensing areas of the Tekscan 6900 sensor with reference system.

3M Micropore™ surgical tape (hereafter referred to as tape) was used to affix the Tekscan sensors to the seats, and to the participants. This tape is thin, hypoallergenic, and is easily removed from the skin and the sensors after use.

If discomfort was present duringa rowing trial, then the degree of discomfort experienced was assessed using a questionnaire. In order to avoid response bias, the participants were instructed to fill out the discomfort survey only if discomfort was present. In order to monitor changes in our participants, a within-subject design is appropriate for effective questionnaire use (Pearson, 2009).

The discomfort associated with pressure-related tissue injury should be noticeable by physically attuned rowing athletes. The Tool for Assessing Wheelchair disComfort(TAWC, formerly known as the WcS-DAT), provides a valid method of quantifying seating discomfort in long-term wheelchair users (Crane et al., 2004). The TAWC was developed with its intended use for wheelchair seating discomfort evaluation, and is adapted for use in the present study. Crane et al. (2005) haveestablished concurrent validity of the TAWC against two commonly used seating evaluation tools; the Chair Evaluation Checklist (CEC) and the Short-form McGill Pain Questionnaire (SF-MPQ) which is used to evaluate seating discomfort on chairs and pain in multiple parts of the body, respectively. Further, the TAWC was tested to be highly stable, internally consistent, and to reliably measure wheelchair seating discomfort (Crane et al., 2005). Further, no significant floor or ceiling effects were found while testing the TAWC (Crane et al., 2007a). In addition, the TAWC is sensitive to monitor changes over time with seating interventions, and stable when changes were not expected (Crane et al., 2007b) making it appropriate for repeated measures methodologies. The TAWC was created with the intention of it being utilised to develop seating technologies (Crane et al., 2003), and has been used successfully to develop a seating intervention for wheelchair users (Crane et al., 2007a). The TAWC employs one relevant component; a General Discomfort Assessment (GDA), which was usedby itself for this studyDiscomfort survey (Appendix A).

Due to the constraints of the National Team training schedule, the participants were only able to commit a single short period of time for testing. Therefore, both comfortable and uncomfortable seat test trials had to be conducted during one session. Each participant was first tested using the seat self-reported as most comfortable. This decision was made to minimise any possible discomfort to the buttocks that a rower could experience during the test that could influence the uncomfortable seat tests. In addition, a ten minute break was given between the comfortable and uncomfortable seat trials for recovery. Both measures were taken in order to minimise the risk of order effects.

This study is concerned with prolonged rowing at an endurance pace. Race situations are of short duration, and were not reported by participants to cause discomfort. Pressure injury was communicated to result from repetitive rowing cycles during training, where the participants will row for several hours per day at an endurance pace (Nolte, V., Personal Communication). As a result, the participants were instructed to row at an endurance pace of twenty strokes per minute during the test trials.

4.3 Definition of research variables

In order to study the relationship between externally applied pressure patterns and discomfort, a number of seats were utilised along with the GDA.

i. The independent variable is defined as the model of seat affixed to the rowing ergometer.
ii. The first dependant variable is defined as the presence or absence of discomfort. If discomfort exists, then it is quantified using the GDA score.
iii. The second dependant variable is defined as the peak IP measured.
iv. The third dependant variable is defined as the maximal IP gradient calculated.

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iv. The third dependant variable is defined as the maximal IP gradient calculated.

4.4 Pre-tests

Four pre-tests were conducted in order to determine the parameters needed to conduct the test trials.

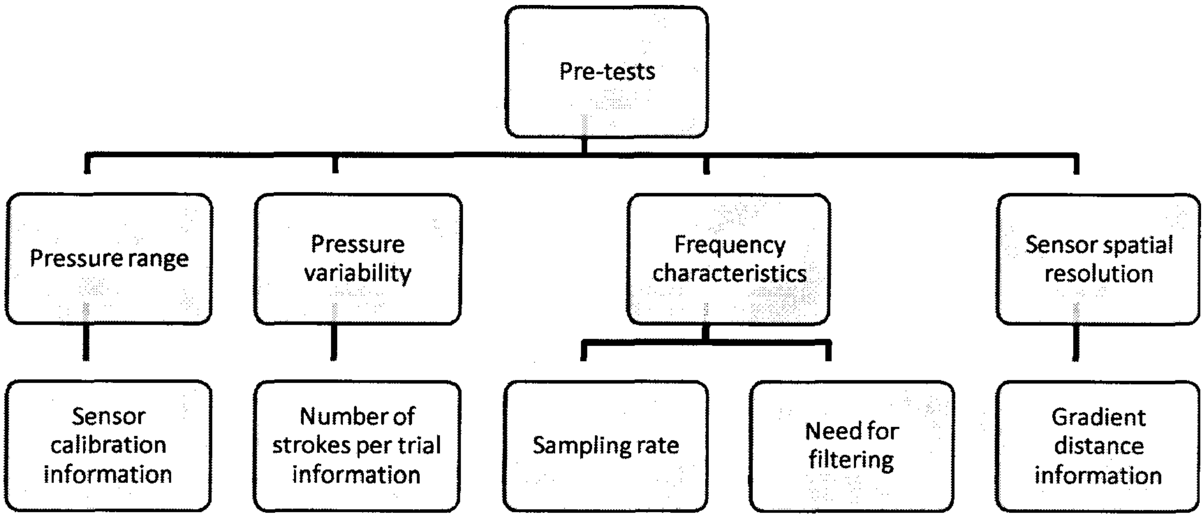

Figure 14 Block diagram illustrating the organisation of pre-tests and the corresponding goals.

4.4.1 Pressure range and sensor calibration

The maximal body-seat IPs produced during rowing were previously unknown. In order to calibrate the Tekscan sensor, the pressure range values needed to be determined.

The Tekscan sensor was initially calibrated to detect its maximum pressure range (0-6895N/cm^2). Seat 3 was selected as it had prominently sharp edges that would potentially concentrate pressure. The participant was then instructed to warm up for five minutes using seat 3. The Tekscan sensor was then affixed to the seat on the outer perimeter and seat holes edges where IP would concentrate using tape (Figure 15).

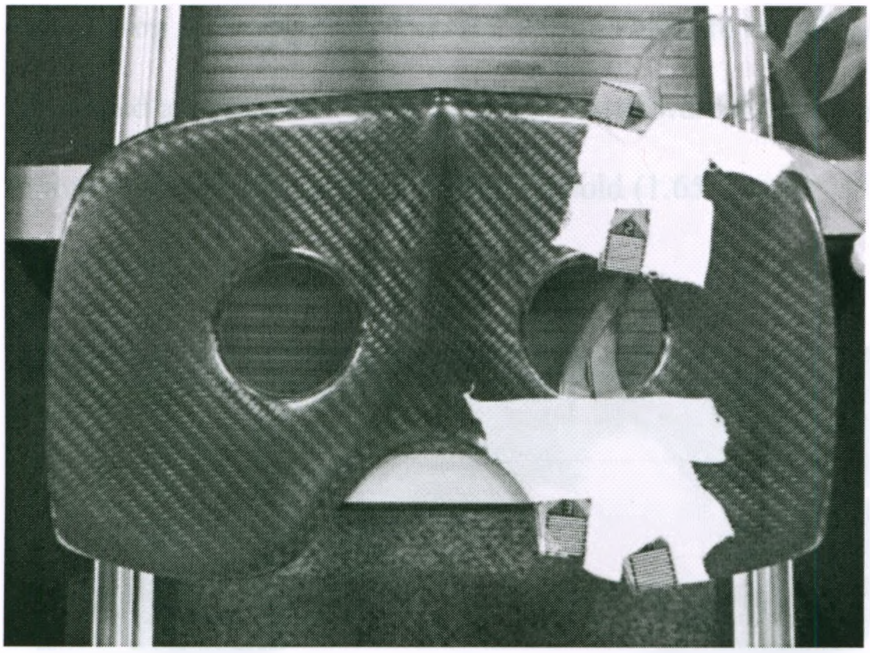

Figure 15 Seat 3 with Tekscan sensors affixed to seat hole and perimeter edges using Micropore™ tape.

The Tekscan sensor pack was affixed to the participant's thigh using tape (Figure 16).Then the participant was instructed to row at an endurance pace of twenty strokes per minute for sixty seconds, during which time data were collected. Since the IP variability was unknown at this stage of the study, sixty seconds of data collection provided a sufficient number of strokes to determine the maximum possible IP. At this time, the frequency content of body-seat IP data during rowing was unknown. The Tekscan system sampled at its maximal rate of 100Hz.

The pressure data werethen examined to determine the maximum pressure measured on any of the four sensing areas during the trial.After determining the maximal measured IP, the Tekscan sensor was then recalibrated to detect a pressure range twice that measure. This allowed for the possibility of measuring unexpectedly large subsequent pressures. Further, the recalibration used less than 6% of the sensor's pressure sensing range. This afforded the sensor a high degree of sensitivity for this application. Using known masses placed atop the sensor, the Tekscan I-Scan software contained a calibration utility that calculated a calibration curve. The I-Scan software determined the saturation pressure (356.43 N/cm^2) and lower discard threshold (1.65N/cm^2).

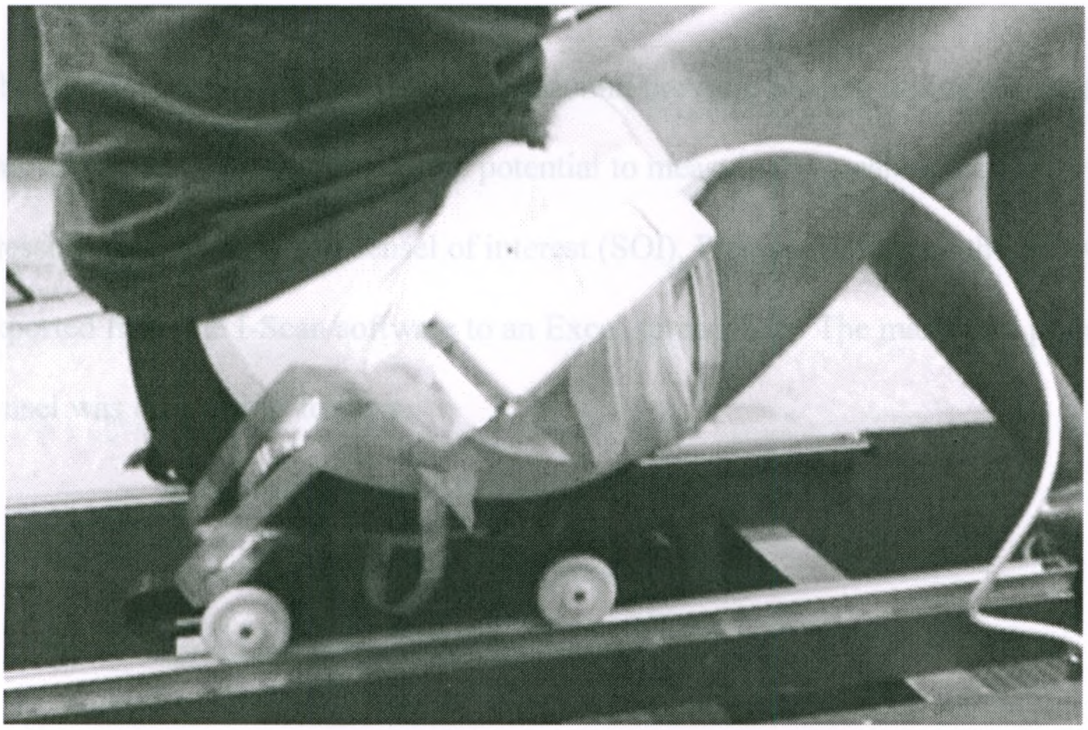

Figure 16 Tekscan Evolution sensor pack affixed to the participant's thigh, with 6900 sensor attached to the seat

4.4.2 Pressure variability

The variability of the pressure readings from the Tekscan sensor was calculated over several strokes in order to determine if a single stroke is sufficient for subsequent tests.

In order to do so, a participant was instructed to warm up for five minutes using a seat self-reported to be uncomfortable. This would conceivably allow maximal pressures to be measured.Using tape, the Tekscan sensor was then affixed to the rowing seat on a sharp edge where pressure would be concentrated (Figure 15). The Evolution sensor pack was affixed to the participant's thigh using tape (Figure 16). The participant was instructed to row at the endurance pace for sixty seconds, during which time the re-calibrated Tekscan sensor measured IPs.

The sensing point that measured the maximum pressure reading during the eight strokes was identified. This sensel had the potential to measure the greatest variability in pressure, and was thus the sensel of interest (SOI). Pressure data from the SOI were exported from the I-Scan software to an Excel spreadsheet. The maximum pressure sensel was detected as follows:

$$MaximumPressure = MaxValue(S1 \dots Sx) \quad (1)$$

S1 = First sensel detecting pressure change.

Sx = Last sensel detecting pressure change.

The pressure data were examined to identify a marker for sectioning the data into individual strokes. A clearly repetitive event was identified that occurred during each stroke. The frame at which the IP magnitude began to increase continuously until its peak without decreasing was the repetitive event used.

After sectioning data into14 individual strokes, the data from each stroke were normalised to a scale of 0 – 100% stroke (100 frames) by linear interpolation using a pre-made Excel macro (Robertson, 2011). This step allowed for data point comparisons at each point in time across strokes.The coefficient of variation (CV) was calculated for each of the 100 frames across trials, and the maximum CV was identified.

$$CV = \frac{\sigma}{\bar{x}} \times 100 \qquad (2)$$

σ = Standard deviation

$\bar{x}$ = Mean

4.4.3 Frequency characteristics and sampling rate

Body-seat IP mapping had not been previously performed during rowing. The noise and frequency characteristics of the pressure data needed to be assessed in order to determine the sampling rate necessary to capture peak pressures, and the appropriate filtering method, if one is needed. Two methods were used to determine the sampling rate needed; a Fast Fourier Transform (FFT) and a manual down-sampling of the pressure data.

The participant was instructed to warm up for five minutes using the seat self-reported as most uncomfortable. The Tekscan sensor was affixed to the rowing seat on a sharp edge using tape (Figure 15).The Evolution sensor pack was affixed to the participant's thigh using tape (Figure 16). The participant was instructed to row at the endurance pace for five seconds (the variability test indicated that a single three second stroke was sufficient for analysis). During which time IP data were collected at the Tekscan system's maximal sampling rate of 100Hz. Since collecting IP data during a precise time frame for one stroke was not possible; five seconds permitted the collection of at least one complete stroke.

Pressure data from the SOIwere isolated and exported to an Excel spreadsheet. The Fourier Analysis function in the Excel Data Analysis Pack (Microsoft Corporation) was used to calculate the FFT. In order to run the FFT, a binary number of data points was needed. The IP data was padded with zeros at the end of the data set to fill 512 data points to accomplish this.A plot of the frequency and magnitude was examined to determine to highest frequency present with power. In accordance with the Nyquist theorem, a frequency of twice the highest frequency identified with power was set to be the minimum sampling rate for this study; however, this sampling rate would have been insufficient to record peak IP values.

Manual down-sampling of pre-test data was performed in order to verify the validity of peak IP data at a series of sampling rates. In order to do this, the data from the SOI from the FFT test were exported to an Excel spreadsheet. The original data were sampled at 100Hz. To down-sample to 50Hz, every second data point was extracted from the original data.To down-sample to 33.33Hz, every third data point was extracted from the original data.To down-sample to 25Hz, every fourth data point was extracted from the original data.Down-sampled data were then examined for visible aliasing and loss of peak IP values. Loss of either wave shape or peak values indicated the sampling rate should be greater.

The noise characteristics of the pressure data needed to be evaluated in order to determine whether or not the pressure data required filtering prior to analysis. To do this, a sample frame of data containing four 11x11 matrices of data points (one from each of the four Tekscan sensing areas) from the frequency content test was used for the calculation of the IP gradient distribution. The frame at which the peak pressure occurred was selected for use, as it has the potential to contain an extreme IP gradient.

The IP data were exported to an Excel spreadsheet, where they were arranged in four 11x11 matrices. Each Excel cell contained data from a single sensing point. The formula for IP gradients is as follows:

$$IPGradient = \left|\frac{P(S1)-P(S2)}{Dh(orDd)}\right| (N/cm^2/mm) \quad (3)$$

PS1 = pressure from sensel registering pressure

PSx = pressure from adjacent sensel (vertically, horizontally, or diagonally) registering pressure

Dh = the distance from the center of a sensel to the center of the horizontally or vertically adjacent sensel

Dd = the distance between the center of a sensel to the center of the diagonally adjacent sensel

Excel was used to calculate the IP gradients. In the first step of the algorithm, IP gradients were calculated between cells horizontally adjacent to each other. For each sensing point, the algorithm scanned the adjacent cells in both the +x and –x directions and reported the absolute value of the maximal gradient for each cell regardless of direction. The absolute value is used because the sensor placements on the rowing seats were irregular, and not aligned to any coordinate system. Thus, gradient directions could not be calculated. This step returned the maximal IP gradient at each given sensing point per 1.27mm in the x-axis.

IP gradients were then similarly calculated in the vertical direction, returning IP gradient calculations per 1.27mm in the y-axis.IP gradients were then similarly calculated in the diagonal directions, however this step returned IP gradient calculations per 1.80mm. The spacing of the sensing points was larger in the diagonal direction than in the horizontal direction. To return IP gradient calculations over the same distance as the horizontal and vertical calculations, each calculated IP gradient was multiplied by a correction factor of 0.7071 . The correction factor was calculated as follows:

$$Correctionfactor = \frac{Dh}{Dd}\ (nounits) \tag{4}$$

The algorithm then scanned the IP gradient calculations at each sensing point in all directions, and reported the maximum IP gradient, regardless of direction. The reported gradients were arranged in four 11x11 matrices creating a maximal IP gradient distribution, one matrix per sensing element.

Finally, the IP gradient distribution map was examined qualitatively to assess the smoothness of the spatial changes in maximal IP gradient.

4.4.4 Sensor spatial resolution

The Tekscan sensor was tested to assess the sensor's ability to distinguish between a large force on one sensel, and a zero force on the adjacent sensel. The ability of the sensor to do so successfully would verify our ability to detect very large IP gradients between two adjacent sensing points.

In order to do this, one of the four sensing areas of the Tekscan sensor was placed on a clean, flat, hard surface. A hard rubber cylinder (7mm in diameter) was then used to exert an arbitrary amount of pressure on the sensor by hand. During this time, the sensor collected pressure data at 50Hz. The data were examined for pressure readings on sensels located outside of the 3.5mm radius of sensor-cylinder contact area.

4.4.5 Pre-test results

The Tekscan sensor was calibrated to measure an IP range of 1.65 - 356.34 N/cm^2. The lower discard threshold determined by the I-Scan software for this calibration was 1.65 N/cm^2.

The maximal CV calculated was 11.6% (Figure 17). Although the individual stroke IP data werelinearly interpolated (2-point interpolation), differences in the timing of each phase of the stroke were expected even from an elite rower. As a result, the coefficient of variation may be inflated. A CV of 11.6% permits the use of a single stroke for analysis.

The highest frequency component of the pre-test data was 4Hz (Figure 19). As per the Nyquisttheorem, the sampling rate could not be less than 8Hz. The down-sampled IP data showed no visible loss of the IP wave shape at 25Hz (Figure 19). However, temporally shifting the re-sample one frame forward in time would have resulted in a different data

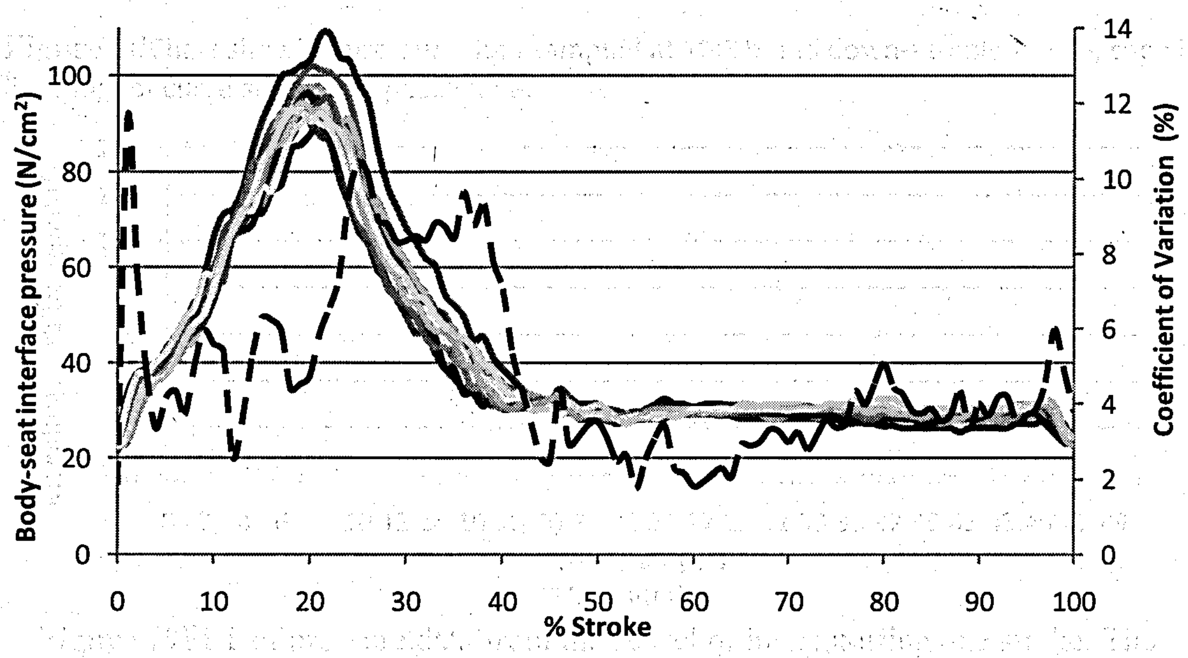

Figure 17 Graph showing interface pressure readings from the SOI for 14 strokes using one rower. As illustrated by the solid line curves, the variability between strokes was small. The variation is described by the coefficient of variation curve (dashed line).

set, and the loss of the peak IP measure at both 25Hz and 33.33Hz. At 50Hz, temporally shifting one frame forward did not result in the loss of peak IP (Figure 18). Each frame contains 484 data points. At fifty frames per second for approximately three-seconds per trial, each trial consisted of 72,600 data points. More than 72,600 data points per trialwould make analysis arduous. Thus, 50Hz was established as the sampling rate.

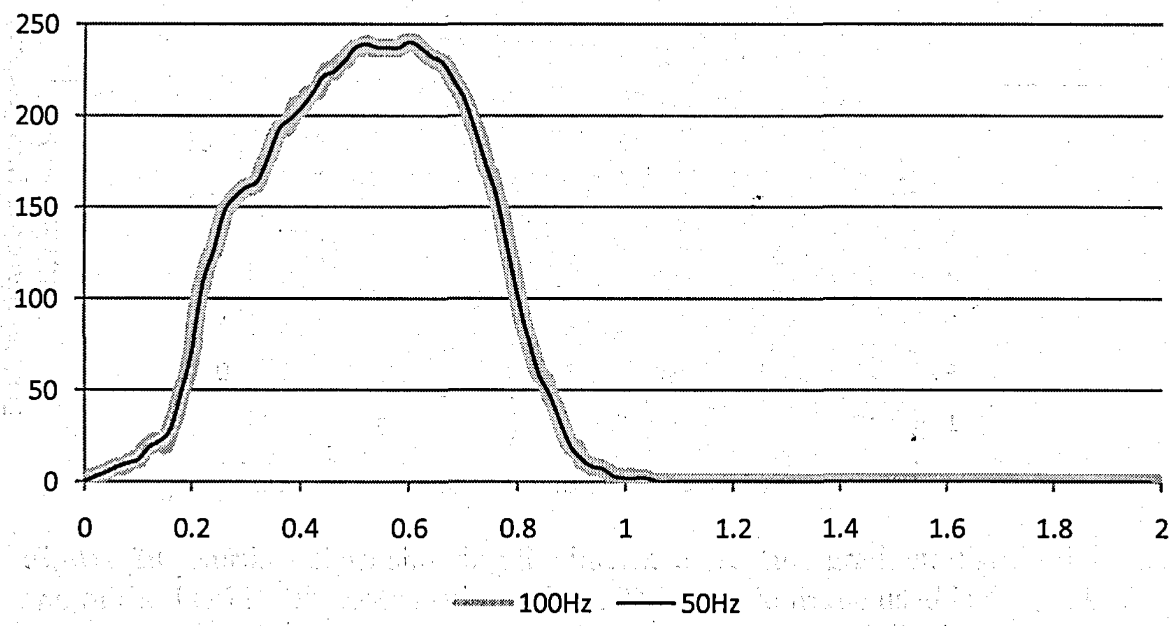

Figure 18 Chart showing pressure data sampled at 100Hz and down-sampled to 25, showing little loss of curve shape and peak value.

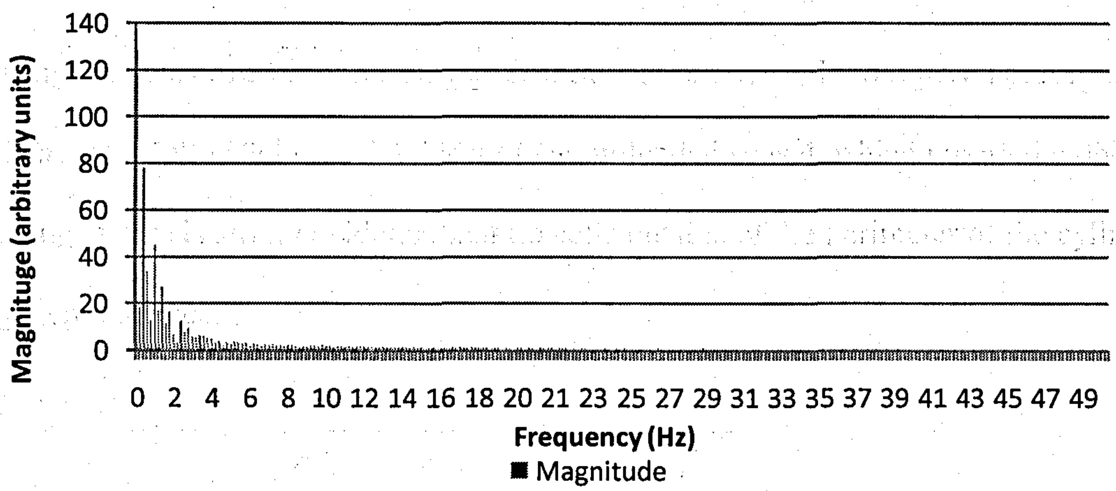

Figure 19FFT of pressure data from the sensel of interest using one stroke. The chart shows frequencies with power up to 4Hz. Frequency magnitudes above 4Hz are indicative of noise

The 3-dimensional pressure maps showed smooth changes in IP over distance (Figure 20). The absence of noisy pressure readings permits the use the pressure data for gradient calculation without smoothing.

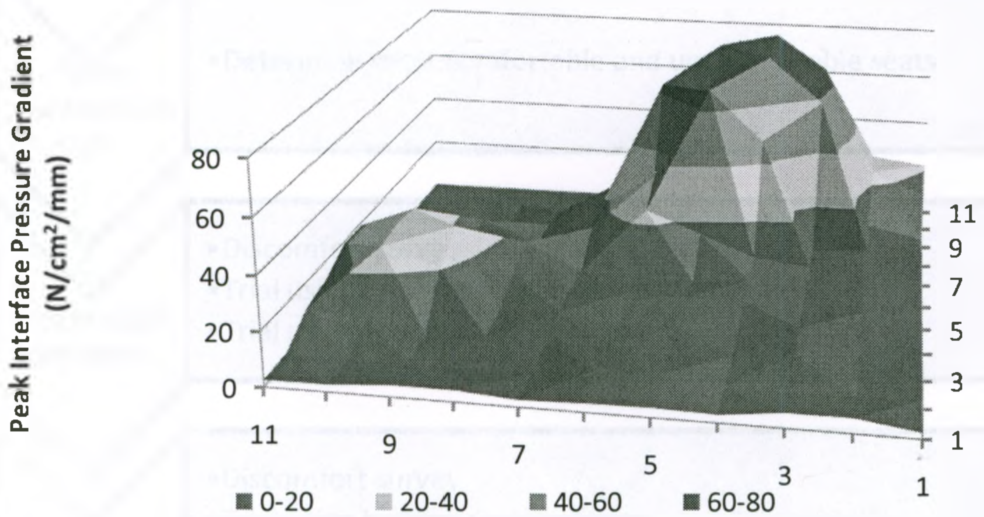

Figure 20 Surface chart showing the interface pressure gradient distribution across one of the 11x11 Tekscansensel matrices. The sample frame used is the peak IP frame. The matrix illustrates the smoothness of the pressure gradient distribution.

During the sensor resolution test, the Tekscan sensor was able to report a pressure of 332N/cm^2 on a loaded sensel adjacent to an unloaded sensel, which reported a 0N/cm^2 reading. There is strong evidence that no cells outside of the perimeter of the cylinder registered a force.

4.5 Test-trial protocol

The test-trials utilised seats self-reported by the participants as either comfortable or uncomfortable. Data to be used for calculating the correlations between discomfort and peak IP, and between discomfort and maximal IP gradient were collected as follows:

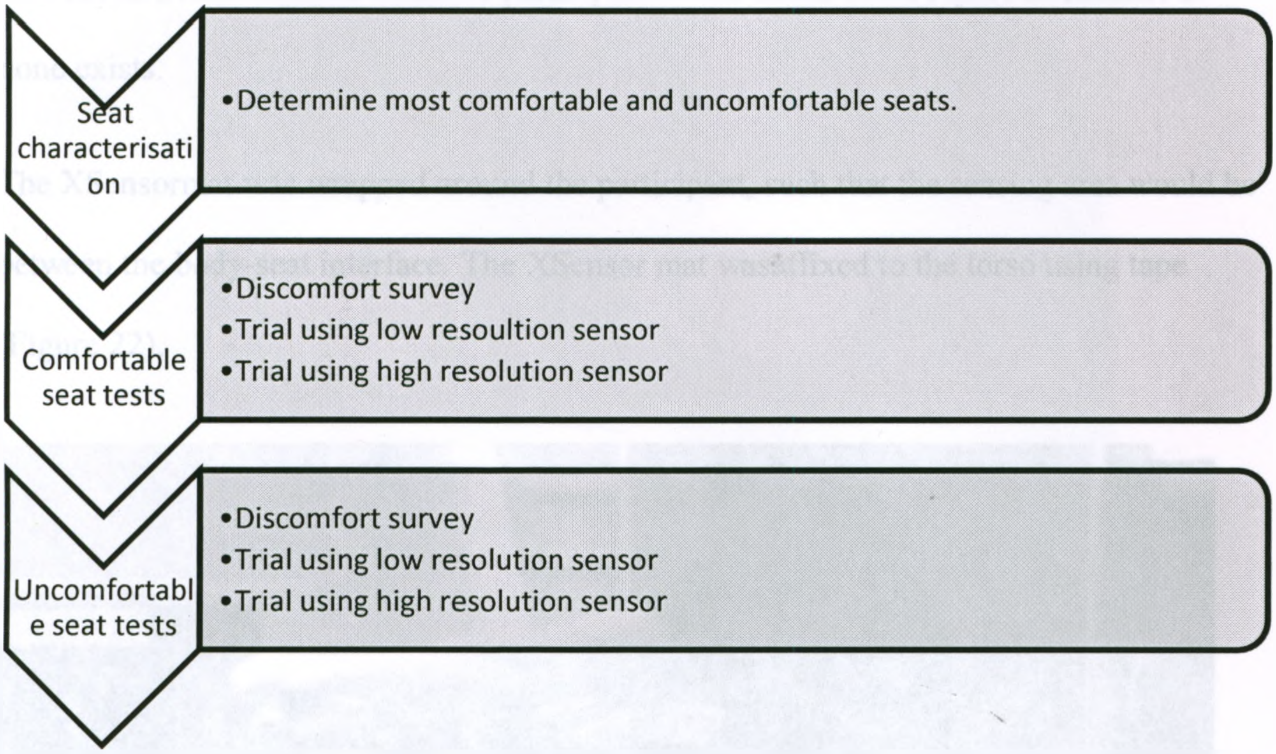

Figure 21 Test-trial protocol flow chart

Participants were asked to carefully read the consent form (Appendix B), and sign it if they agreed to participate in the study.During the test-trials, participants were instructed to row at the endurance pace using a normal form.

The participants initially used all six seats for one minute each, and reported the most comfortable and least comfortable seat. The participant then warmed up using the most comfortable seat for 5 minutes, without the use of a pressure sensor. The participant was instructed to pay attention to sensations arising from the seat. If the participant felt discomfort arising from the seat, the discomfort questionnaire was administered, and the GDA scores were recorded. The discomfort survey contained a blank picture of the seat the participant used and a GDA (Appendix A). The participants were asked to circle areas of the picture demarcating areas of perceived areas of discomfort on the seat (Figure 23). In order to avoid response bias, the participants were asked not to report discomfort if none exists.

The XSensormat was wrapped around the participant, such that the sensing area would be between the body-seat interface. The XSensor mat wasaffixed to the torso using tape (Figure 22).

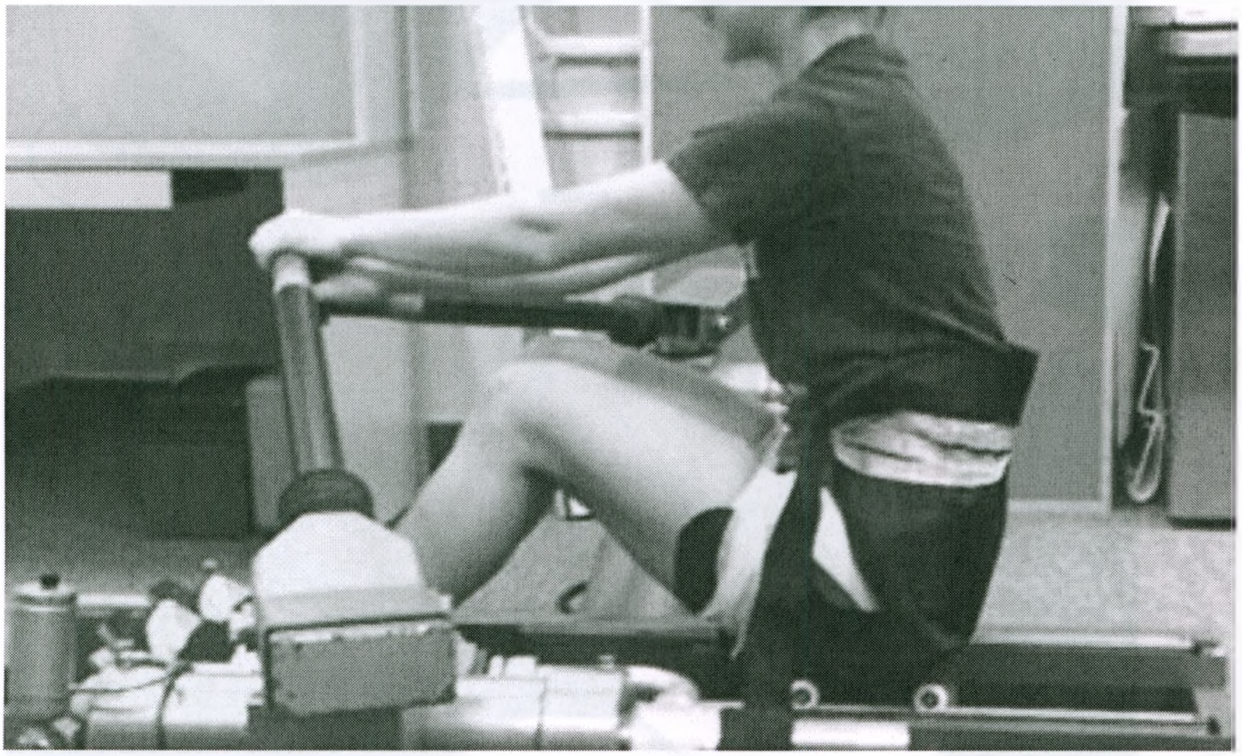

Figure 22 Photograph showing the XSensor mat affixed to the rower

The rower was instructed to row while IP data were collected at 50Hz using the XSensor mat for twenty seconds. Twenty seconds of rowing permitted the investigators to qualitatively assess areas of high IP.The XSensor mat was removed from the participant, and the participant was given a ten minute rest period.

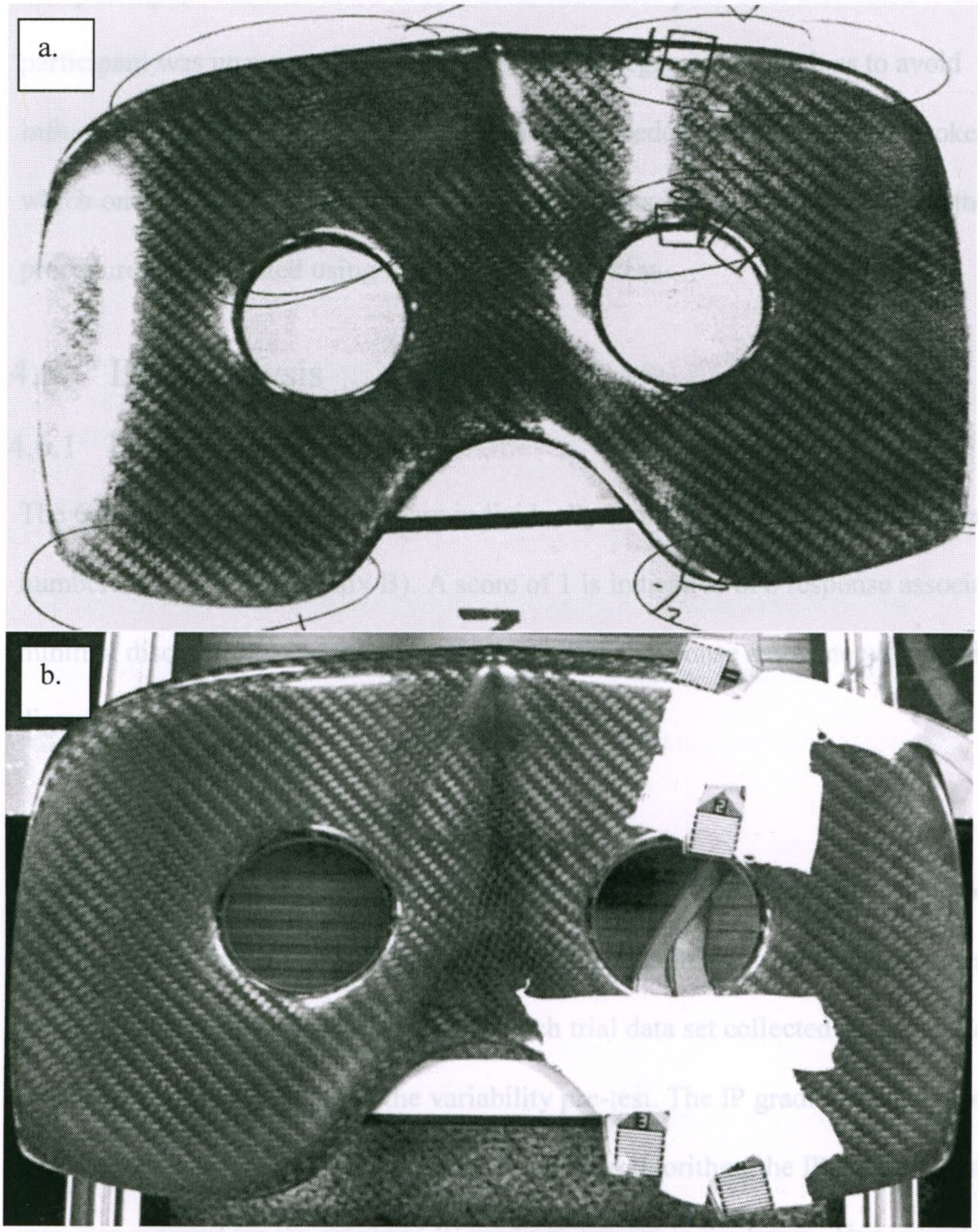

Figure 23a.Example of an actual Participant Survey diagram showing circled areas of perceived discomfort filled out by a participant. Squares indicate potential sensor placement. b. Seat with corresponding arrangement of Tekscan sensors affixed to areas of perceived high pressure, in this case, the edges of the holes and outer perimeter.

The Tekscan sensor was affixed to areas of the seat that the XSensor mat data indicated as areas of high IP. If the XSensor data did not indicate areas of high IP, the participant's diagram was used to determine Tekscan sensor placement (Figure 23a).

The participant was instructed to row at an endurance pace until instructed to stop. The participant was unaware of when data collection began or finished, as to avoid influencing the rowing form. Data collection proceeded over five rowing strokes, from which one stroke was selected randomly for analysis. After a ten minute rest, the procedure was repeated using the uncomfortable seat.

4.6 Data analysis

4.6.1 Discomfort data analysis

The GDA component questions are individually scored according to a Likert scale using numbers from 1-7 (Appendix B). A score of 1 is indicative of a response associated with minimal discomfort. A score of 7 is indicative of a response associate with maximal discomfort.

4.6.2 Trial data analysis

Data collected during the test trials were used to calculate the pressure change per millimetre between every two adjacent sensing points in the array.One stroke was randomly selected and isolated from the each trial data set collected using the Tekscan sensor using the same method the variability pre-test. The IP gradient calculations used in the pre-tests were repeated. In the final step of the algorithm, the IP gradient distribution map was scanned for the maximal IP gradient present in the frame. This value indicated the maximal IP gradient.

Maximal IP gradient calculations and peak IP measures for each trial were recorded in a spreadsheet with the GDA scores. The GDA is scored by tabulating the sum of the 7 point Likert scale scores from its individual items. A stepwise linear regression was calculated in order to determine the variance in GDA score explained by IP. Two independent variables and one dependent variable were defined:

a. Independent variable 1: The peak IP measured in each trial
b. Independent variable 2: The maximal IP gradient calculated in each trial
c. Dependant variable: GDA score in each trial

A criterion r-value for supporting the hypotheses was set at $r = 0.707$, such that 50% of the variation in discomfort is attributable to the maximal IP gradients or the peak IP measures.

The coefficients of determination for both correlations calculated were used to calculate the observed statistical power using an existing statistical calculator (Soper, 2011) in order to make suggestions for future study. The following criterions were used:

α-level: 0.05

Observed r^2: r-values calculated raised to the power of 2

$n = 11$

4.6.3 Post-hoc analysis

Two post-hoc testswere performed to determine the sample size needed if the test-trials were to be repeated. The r^2calculated between peak IP and GDA score were used, given that the correlation between GDA score was weaker with peak IP than maximal IP gradient. An existing statistical calculator was used (Soper, 2011). The following criteria were used:

α-level: 0.05

Desired power level of 0.8

$r^2 = 0.18$

A two-tailed paired t-test was then performed to determine if significant differences existed between GDA scores corresponding to comfortable and uncomfortable seats. This was performed using the Excel Data Analysis Pack (α-level = 0.05).

A two-tailed paired t-test was again performed to determine if significant differences existed between maximal IP gradient means from two groups; comfortable and uncomfortableseats. The test was repeated to determine if significant differences existed between peak IP means using the same grouping. This information is intended to supplement the primary findings and be used only to make general inferences about potentially desirable and undesirable characteristics of the rowing seats used in this study.

Mean maximal IP gradient calculations were then tabulated from the test trials in a spreadsheet, and divided into two groups; comfortable and uncomfortable seats. A two-tailed paired t-test comparing maximal IP gradient meansof the two groups was performed (α-level = 0.05). The test was repeated using peak IP measure means.

4.7 Advantages of research design

Advantages of the research design include the avoidance of practice effects. This is accomplished by the use of expert rowing athletes, who already perform with a high level of proficiency, and the likelihood of form improvements during the study is extremely low. Additionally, the participants' familiarity with proper rowing technique negates the need for a familiarization period. Further, the experiment was performed indoors, avoiding the confounding effects of wind, unsteady waters, and uncomfortable temperatures on the participants' form.

5. Results

5.1 Interface pressure and discomfort

Discomfort from the rowing seat was reported in all trials when using all rowing seats. The participant survey was administered for every trial. The peak IP measured using comfortable seats ranged from 10.71 to 88.61 N/cm^2 (Table 2), and from 52.44 to 287.46 N/cm^2 (Table 4) using uncomfortable seats. Maximal IP gradients calculated using comfortable seats ranged from 8.43 to 46.80 N/cm^2/mm (Table 2), and from 37.05 to 213.17 N/cm^2/mm using uncomfortable seats (Table 4). Seat comfort rankings are shown in Table 4.

GDA scores pertaining to seats deemed comfortable ranged from 21 – 58 (Table 2), and from 55 – 85 (Table 3) when using uncomfortable seats.

Table 2 Discomfort scores, seat numbers, and pressure information for comfortable seats

Participant #	Previous injury	Seat # chosen	GDA Score	Peak IP gradient (N/cm^2/mm)	Peak IP (N/cm^2)
1	Yes	4	25	20.69	28.29
2	No	1	27	42.59	78.21
3	Yes	4	39	46.8	74.39
4	Yes	1	21	13.9	26.27
5	Yes	4	41	19.13	28.29
6	Yes	4	30	40.76	57.16
7	Yes	4	56	12.47	18.57
8	Yes	5	27	15.94	34.53
9	Yes	3	58	8.43	10.71
10	Yes	6	41	33.13	88.61
11	Yes	4	47	28.08	41.05

Table 4 Discomfort scores, seat numbers, and pressure information for uncomfortable seats

Participant #	Previous Injury	Seat # chosen	GDA Score	Peak IP gradient ($N/cm^2/mm$)	Peak IP (N/cm^2)
1	Yes	6	70	41.44	69.37
2	No	6	85	49.04	71.87
3	Yes	1	66	96.42	127.15
4	Yes	5	55	56.62	85.99
5	Yes	6	73	119.02	159.48
6	Yes	6	60	52.43	103.37
7	Yes	3	72	37.05	52.44
8	Yes	6	63	91.82	287.46
9	Yes	6	62	213.17	125.72
10	Yes	3	68	57.63	91.26
11	Yes	3	73	100.33	131.46

Table 3 Seat comfort rankings for each participant. Seats are ranked from most comfortable to least comfortable (left to right).

	Ranking					
Participant	Most comfortable			Least comfortable		
1	4	3	1	2	5	6
2	1	5	4	2	3	6
3	4	5	1	6	3	2
4	1	4	2	3	6	5
5	5	4	2	1	3	6
6	4	1	3	5	2	6
7	4	5	1	3	6	2
8	5	4	2	3	1	6
9	3	1	2	5	4	6
10	6	2	5	4	1	3
11	4	5	1	2	6	3

5.2 Pressure distribution

The perimeter of the seat holes were identified as regions of high pressure in 9 of the 11 comfortable seat trials, however participants reported them as sources of discomfort in all 11 trials. The perimeters of the seat holes were identified as regions of high pressure in 10 of the 11 trials using uncomfortable seats; these areas were self-reported as sources of discomfort in all 10 of those trials (Figure 25).

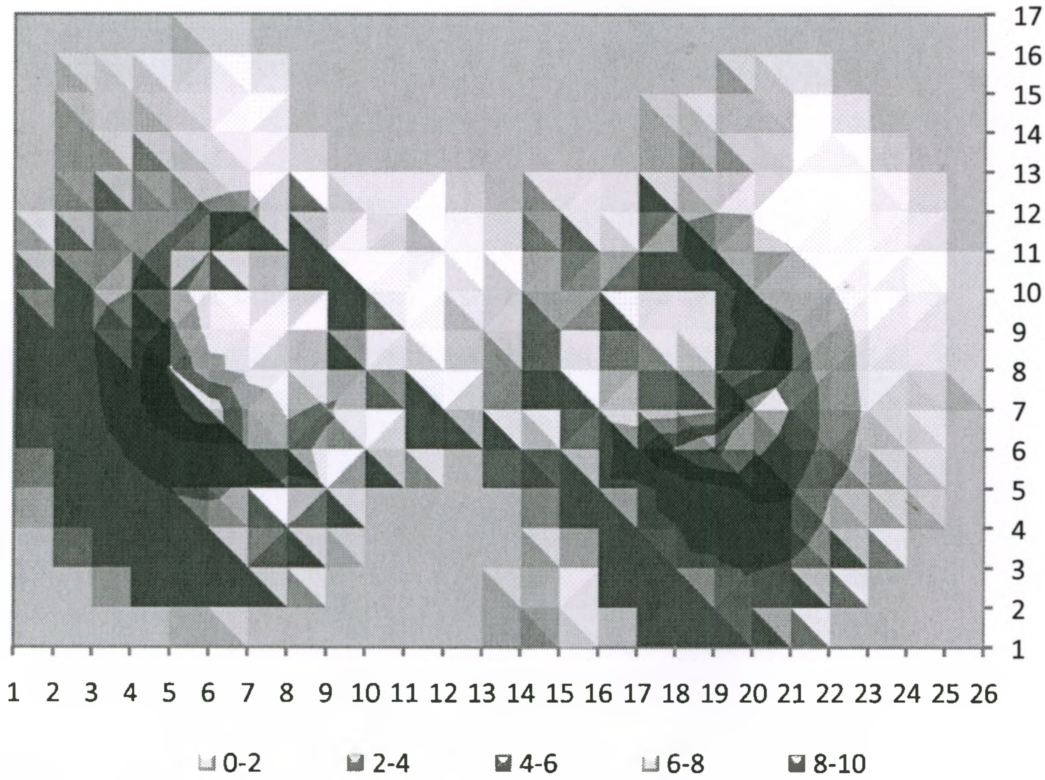

Figure 24 Topographical IP map of an XSensorsensel matrix (17x 26 sensels shown) using a seat reported as most comfortable. The map shown illustrates that pressure is concentrated around the perimeter of the holes at the catch position. Pressure values are in units N/cm^2.

The outer perimeter of the comfortable seats were identified as regions of high pressure in 5 of the 11trials, however the participants reported the outer perimeter as a source of discomfort in 8 of the 11 trials. The outer perimeter of the most uncomfortable seats were identified as regions of high pressure in 7 of the 11 trials (Figure 26); but were reported by participants as sources of discomfort in 9 trials. One participant reported a convex area between the seat holes as a source of discomfort; however, the peak IP in the area was below the threshold for injury (4.25N/cm^2).

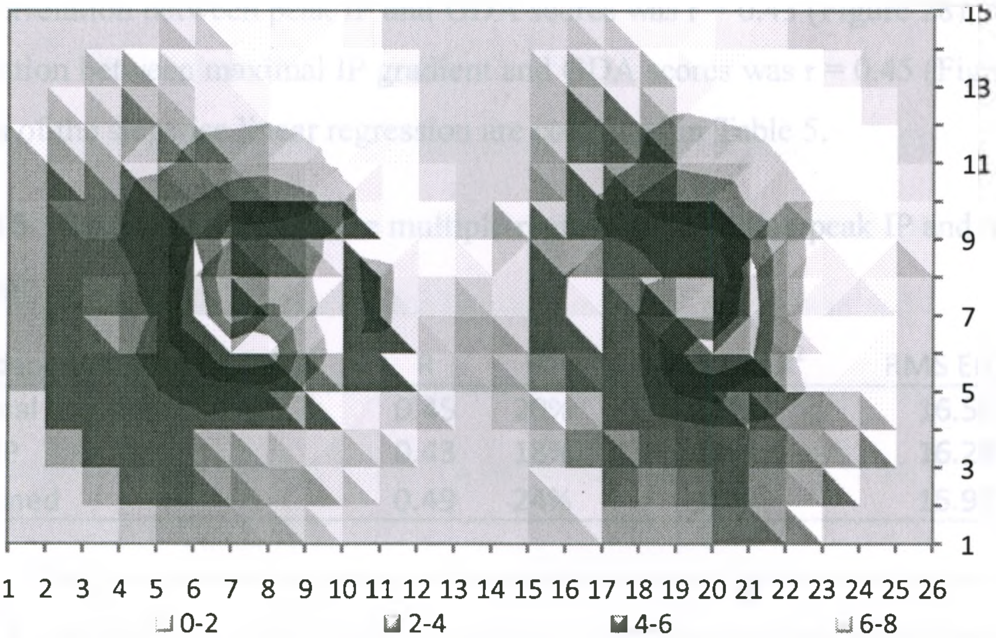

Figure 25 Topographical IP map of an XSensorsensel matrix (15x 26) using a seat reported as comfortable. Pressure is concentrated around the perimeter of the holesduring the recovery phase of the stroke. (N/cm^2).

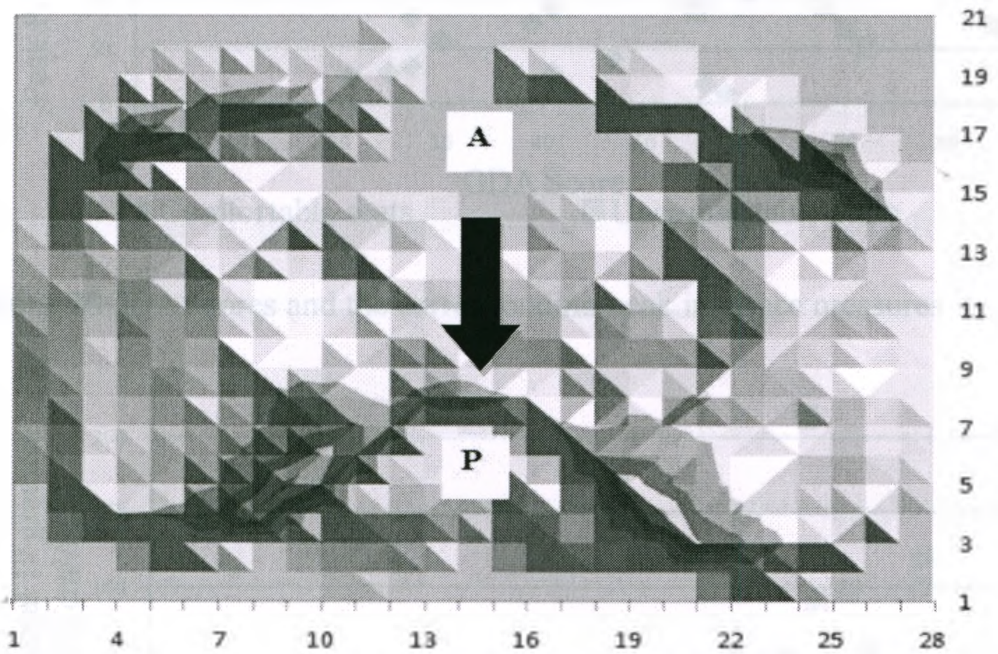

Figure 26XSensor body-seat IP map of 21x28 sensels at the finish position using a seat reported as most uncomfortable. Pressure is concentrated along the outer seat perimeter. The anterior "A" and posterior "P" edges of the seat are marked. Pressure values are in units N/cm^2. The contact point between the coccyx and seat is shown by an arrow.

5.3 Correlations

The correlation between peak IP and GDA scores was r = 0.43 (Figure 28), whereas the correlation between maximal IP gradient and GDA scores was r = 0.45 (Figure 27). The results of the stepwise linear regression are contained in Table 5.

Table 5 Results of the stepwise multiple regression including peak IP and maximal IP gradient.

Independent variable(s)	R	R^2	Adjusted R^2	RMS Error
Maximal IP gradient	0.45	20%	17%	16.50
Peak IP	0.43	18%	14%	16.29
Combined	0.49	24%	15%	15.97

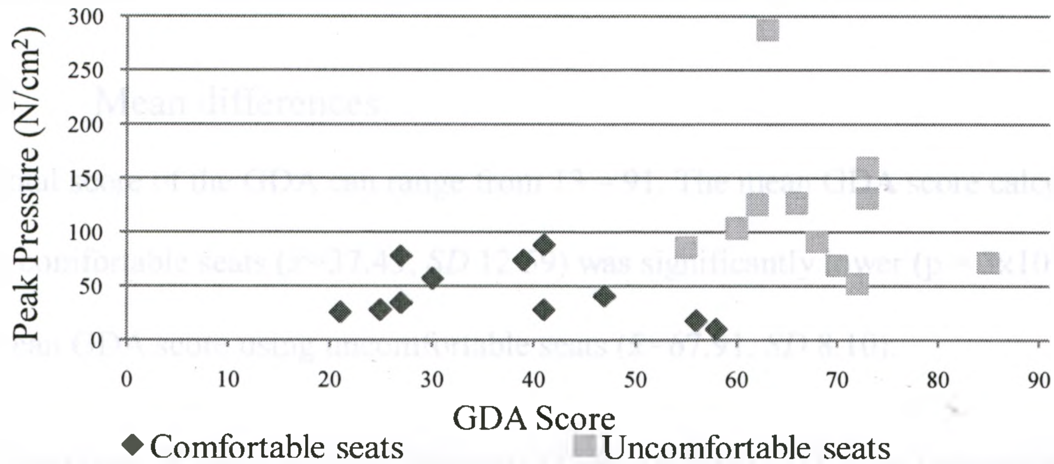

Figure 28GDA scores and the corresponding peak interface pressures

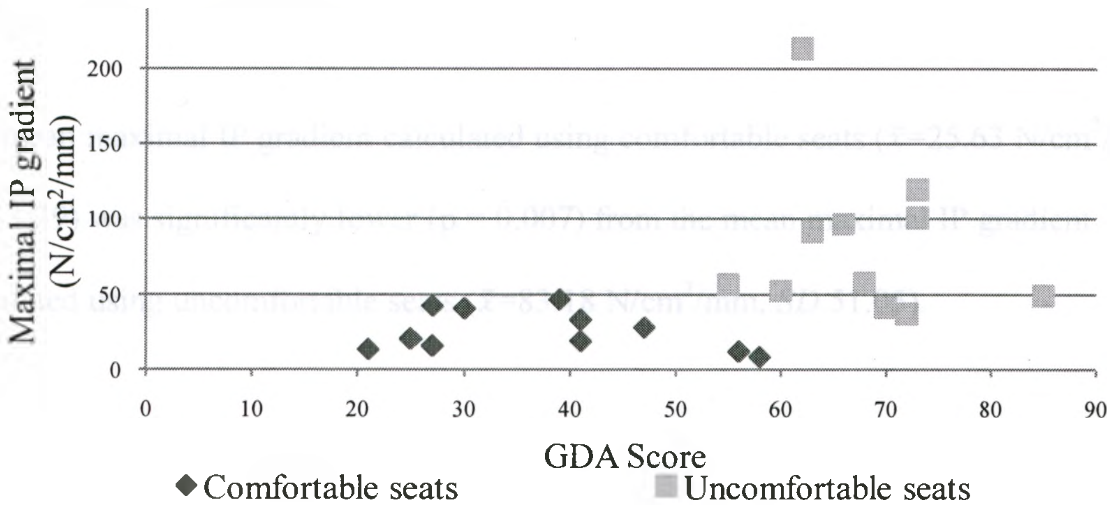

Figure 27GDA scores and corresponding maximal interface pressure gradients

5.4 Post-Hoc Analyses

5.4.1 Statistical power

The observed statistical power for the correlation between peak IP and GDA scores was 0.30. The observed statistical power for the correlation between maximal IP gradient and GDA score was 0.32.The correlation between maximal IP gradient and GDA score was stronger than the correlation between peak IP and GDA score. Given the correlation between peak IP and GDA ($r = 0.43$), a minimum sample size of 36 should be used to repeat this experiment in order to achieve a statistical power level of 0.8.

5.4.2 Mean differences

The total score of the GDA can range from 13 – 91. The mean GDA score calculated using comfortable seats ($\bar{x}$=37.45, *SD* 12.59) was significantly lower ($p = 3x10^{-5}$) than the mean GDA score using uncomfortable seats ($\bar{x}$=67.91, *SD* 8.10).

The mean peak IP using comfortable seats ($\bar{x}$=44.19 N/cm^{2}, *SD* 26.30) was significantly lower ($p = 0.007$) from the mean peak IP using uncomfortable seats ($\bar{x}$=118.69 N/cm^{2}, *SD* 64.42).

The mean maximal IP gradient calculated using comfortable seats ($\bar{x}$=25.63 N/cm^{2}/mm, *SD* 13.39) was significantly lower ($p = 0.007$) from the mean maximal IP gradient calculated using uncomfortable seats ($\bar{x}$=83.18 N/cm^{2}/mm, *SD* 51.05).

5.4 Post-Hoc Analyses

5.4.1 Statistical power

The observed statistical power for the correlation between peak IP and GDA scores was 0.30. The observed statistical power for the correlation between maximal IP gradient and GDA score was 0.32.The correlation between maximal IP gradient and GDA score was stronger than the correlation between peak IP and GDA score. Given the correlation between peak IP and GDA ($r = 0.43$), a minimum sample size of 36 should be used to repeat this experiment in order to achieve a statistical power level of 0.8.

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The total score of the GDA can range from 13 – 91. The mean GDA score calculated using comfortable seats ($\bar{x}$=37.45, *SD* 12.59) was significantly lower ($p = 3x10^{-5}$) than the mean GDA score using uncomfortable seats ($\bar{x}$=67.91, *SD* 8.10).

The mean peak IP using comfortable seats ($\bar{x}$=44.19 N/cm^{2,} *SD* 26.30) was significantly lower ($p = 0.007$) from the mean peak IP using uncomfortable seats ($\bar{x}$=118.69 N/cm^{2,} *SD* 64.42).

The mean maximal IP gradient calculated using comfortable seats ($\bar{x}$=25.63 N/cm^2/mm, *SD* 13.39) was significantly lower ($p = 0.007$) from the mean maximal IP gradient calculated using uncomfortable seats ($\bar{x}$=83.18 N/cm^2/mm, *SD* 51.05).

6. Discussion

6.1 Primary findings: Regressions and power.

The investigators predicted that physically attuned rowing athletes would perceive sharply applied pressure to the buttocks as discomfort. All participants reported discomfort during all trials, including those using seats self-reported as most comfortable. This permitted all trials to be included in the analyses. The criterion r-value of 0.707 was not reached for either IP gradient and GDA score or peak IP and GDA score. The variation in GDA score attributable to maximal IP gradients was 20% (Figure 27), and 18% of the variation in GDA score was attributable to the peak IPs (Figure 28). The findings of this study indicate that a weak but positive relationship exists between discomfort and each of maximal IP gradient (r = 0.45), and peak IP(r = 0.43). While Maximal IP gradient explained more of the variance in GDA score than Peak IP, the relationships between IP and discomfort are insufficiently strong to report a model (Table 5). The combined R^2 (24%) suggests that the addition of peak IP gradient to the maximal IP gradient regression model increases the explained variance in GDA score by 4%. However, the combined adjusted R^2(15%) indicates that there is no additionalvariance in GDA score explained by the addition of peak IP to the model. The small combined R^2 may indicate that the sample size in the present study was insufficient to determine the variances in GDA score explained by peak IP and maximal IP gradient. Given the sharp pressure gradients observed (upwards of 213.17 N/cm^2/mm),the investigators expected stronger relationships between IP gradient and discomfort, and between peak IP and discomfort.

A number of factors may explain the strength of the correlations. Firstly, ten participants communicated a history of superficial and deep pressure-related tissue injuries to the buttocks resulting from contact with the rowing seat (Table 2). Three participants reported permanent bony tissue deformations to the ITs resulting from years of rowing. It is possible that the IP during rowing exceeded the load tolerance of the ITs in our participants, and that these participants have become desensitized to discomfort in the buttocks to some degree. Sanders et al. (1995) suggest that large volumes of mechanical stress in the skin will cause adaptations which reduce the likelihood of discomfort and pressure injury. This may have led the participants to underreport discomfort scores.

Secondly, the body-seat IPs previously associated with tissue injury are upward of 10.67N/cm^2 (Bennett & Lee, 1986), whereas the pressures measured in this study are upwards of 287.46N/cm^2. Additionally, the IPs measured in this study are over one-hundred times that needed to cause localised ischemia, which contributes to pressure injury and tissue damage (Tam et al., 2003; Bennett and Lee, 1986; Bader, 1990). The extent to which the IPs measured in this study exceed the pressures associated with discomfort and injury may influence the participants' perception of discomfort.

The relationships between maximal IP gradient and discomfort, and peak IP and discomfort are weakly positive. Some previous studies have suggested that dispersing body-seat IP is necessary to reduce discomfort (Bennett & Lee, 1986), where others recommend localising pressures under the ITs (de Looze et al., 2003; Gregory, 2004) in order to minimise soft tissue deformation. Given the differences in load tolerance between bony tissues and soft tissues, and the fact that the soft tissues are interposed between the ITs and the seat surface, minimising peak body-seat IP and IP gradients by dispersing pressure is recommended for rowing seats.

The conclusions that may be drawn from the correlations are limited. Given the low strength of the correlations and the sample size of eleven participants, the observed statistical power is low; 0.30 and 0.32 for the correlation between peak IP and GDA scores, and maximal IP gradient and GDA score respectively. In order to make more powerful inferences from IP measures and IP gradient, the statistical power must be improved. Post-hoc analysis revealed that given the correlations between GDA score and peak IP ($r = 0.43$), and between GDA score and maximal IP gradient ($r = 0.45$), a sample size of at least 36 participants should be used ($p = 0.05$; $r^2 = 0.18$).

6.2 Secondary findings: Pressures, IP gradients, and discomfort scores

The IP distribution patterns during rowing are dynamic. High IPs appear moving in the x-axis across the seat holes from approximately mid-recovery phase through to the catch (Figure 24Figure 25), and appear around the seat perimeter at the finish position (Figure 26). It is conceivable that the movement of the ITs over the seat holes are responsible for the high pressures seen midway through the recovery phase when the rower's weight is mostly borne by the seat and the pelvis rotates in the positive direction around the y-axis. At the finish position, the rower's weight is also largely borne by the seat however the upper thighs and superior part of the buttocks are driven into the outer perimeter of the seat.

GDA scores can range from 13-91. Expectedly, the average GDA score was greater ($p = 3x10^{-5}$) using seats reported as most uncomfortable ($\bar{x}$=67.91, *SD* 8.10) than seats reported as most comfortable ($\bar{x}$=37.45, *SD* 12.59). All participants reported discomfort in all trials, necessitating the use of the discomfort survey. The pressure values associated with pressure injury range from 0.4 – 10.67N/cm2, and the value associated with discomfort to the buttocks is 0.58N/cm^2 under the ITs (Bennett and Lee, 1986; Kamijo et al., 1982). The lowest peak IP measured using a seat reported as most comfortable was 10.71 N/cm^2 (Table 2), exceeding the IP values associated with discomfort and injury. Further, peak IP measures were as large as 287.46 N/cm^2 (Table 4) using seats reported as most uncomfortable. Thus, even the lowest peak body-seat IP during rowing in this study far exceeds the pressure values under the buttocks perceived as comfortable (Kamijo, 1984).

The investigators expected and found significantly greater peak IPs when using relatively uncomfortable seats than comfortable seats. This finding is in agreement with that of de Looze et al. (2003) in that greater IPs are associated with greater discomfort.

Further, it has been previously found that localising pressure under bony tissues during normal sitting is more comfortable than dispersing pressure (Gregory et al., 2004). However, the average peak IP gradient while using seats deemed uncomfortable was significantly greater than the average maximal IP gradient using comfortable seats indicating that localising IP is undesirable. Additionally, the large pressures observed in this study (upwards of 287.46 N/cm^2using an uncomfortable seat) far exceed the previously reported comfortable pressure under the ITs (0.58N/cm^2) and the gluteal region (0.3 N/cm^2; Kamijo et al., 1982).Ultimately, our findings do not support redesigning rowing seats to localise pressure under the ITs.

6.3 Seat shape

Seat 4 was self-reported as the most comfortable seat by 45% of participants (Table 3). This seat has a relatively less extreme concavity, is made from carbon fibre, has a relatively large cut-out section to accommodate the coccyx, and the holes are not bored (Figure 8). Further, the edges around the seat perimeter and around the holes are smoothly bevelled. Seat 6 was reported as the most uncomfortable seat by 54% of participants (Table 3). This seat is made from wood, has a relatively extreme concavity, a relatively large cut-out section to accommodate the coccyx, and bored holes. The outer perimeter and hole edges are relatively sharp (Figure 10).

While different models of rowing seats vary in contour and dimensions, the general design across seats is similar. Rowing seat surfaces are topographically varied and often have numerous crests. Pressure is applied to the buttocks non-uniformly. The edges of

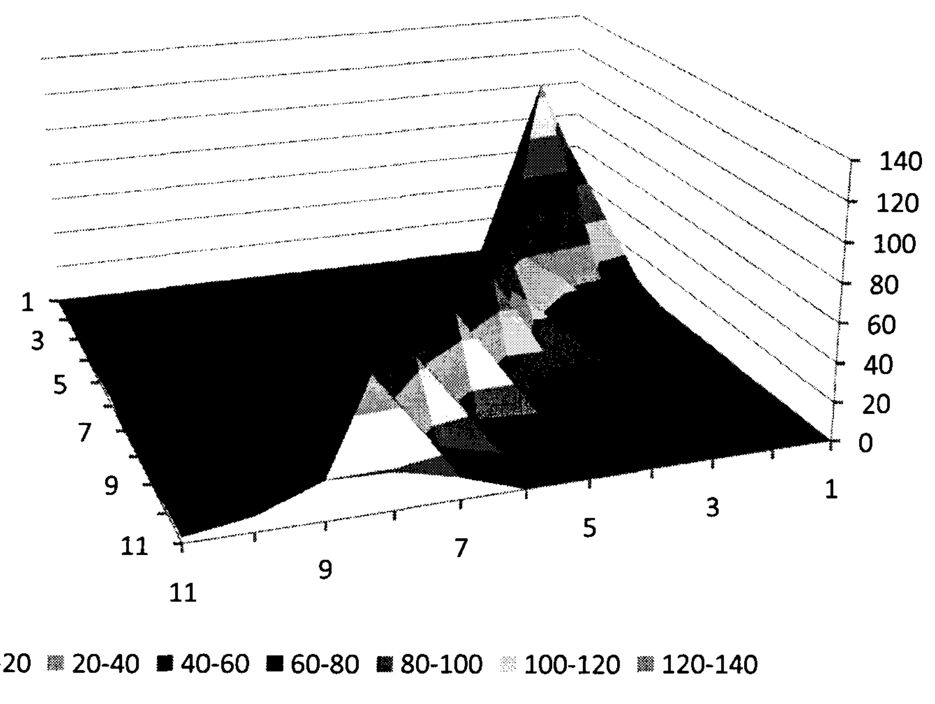

Figure 29 Tekscan sensor pressure map of an 11x11 matrix showing the high pressures along a clearly defined edge of a seat hole.

seat holes were identified as sources of localised pressure and discomfort in 21 of 22 trials, and the outer edges of the seats were reported in 17 of 22 trials. Thus, the seat topography is a factor in user discomfort.

The use of bored holes to accommodate the ITs creates sharp interface contact points, and sources of discomfort. Large pressure measurements are clearly defined along these edges (Figure 29). Spatially, pressures decrease rapidly across sensels increasing in distance from the topographical edge. The sensing points are located 1.27mm apart horizontally and 1.8mm diagonally. The maximal IP gradient calculated was 213.17N/cm2/mm. This indicates that IP can be concentrated within a very small area of the body-seat interface. Despite the low strength of the relationship between peak IP, IP gradients, and discomfort, the participants identified areas of high IP and large IPgradients as sources of discomfort (Figure 23a). Thus,crests and edges are undesirable seat characteristics. Research examining wheelchair seating comfort is divided as to whether or not IP dispersion improves comfort (Stockton &Rithalia, 2009; de Looze et al., 2003). Within the context of rowing, the findings of this study indicate that locallyapplied pressure should be dispersed in order to reduce the peak IP and IP gradients across the seat surface. These findings are unlikely to pertain to other seating applications, given the large magnitudes of IPs measured and IP gradients observed in rowing.

Further, the implementation of circular holes to accommodate the ITs is fallacious. The current general seat design does not properly address the movement of the ITs during hip flexion and extension. The pelvis rotates about the hip in the sagittal plane during hip flexion and extension (Pollock et al., 2009). It is conceivable that the ITs glide along the seat surface in the anterio-posterior direction during rowing, and do not rotate about their inferior surface within the seat holes. All participants communicated that their ITs were abruptly making contact with the hole edges as the ITs moved off of the supportive part of the seat surface. Such an impact is likely to greatly contribute to the high magnitude IPs and IP gradients seen along the edges of the seat holes.

A further complaint reported by participants was interference of normal hip extensor movement, arising from the edges of the seat holes of seats 1 and 6. An "uncomfortable snapping feeling" was reported during hip flexion and extension. The participants reported that the seat hole edges pressed sharply against the ITs during the recovery phase of the stroke, interfering with proper gliding of the gluteal muscles over the ITs. Mechanical distortion of the tissues surrounding the ITs during trunk flexion and extension may increase the potential for damage to the musculature, which may already be ischemic (Koopman et al., 2010)and under shear stress (Bennett & Lee, 1986).

Shear stress in the tissues of the buttocks is an issue arising with non-uniformlyapplied pressure. The shear stress occurring in the buttock tissueis proportional to the pressure gradient at the skin surface (Bennett & Lee, 1986). An average IP gradient of less than $1 N/cm^2/mm$ was reported during neutral sitting in a wheelchair study(Hobson, 1992b). IP gradients as high as $213.17 N/cm^2/mm$ suggest the possibility of a great amount of shear stress in the buttocks.Further, the interference of muscle movement by the ITs due to the seat is likely causing mechanical distortion of the deep tissue in the buttocks.

Blisters on the buttocks are a common complaint among the aforementioned female rowing athletes consulted. Blisters result from the separation of dermal layers caused by shear stress. The outer perimeter of the rowing seat is commonly reported to mechanically abrade the skin as it applies high pressure to the skin where shearing is occurring, causing blisters.

In addition, the buttocks are in constant contact with the seat. As a result, the non-uniformly applied pressure causes the skin of the buttocks and deeper soft tissues to experience shear at all times. Tissues encountering shear stress are particularly susceptible to vascular occlusion (Bennett & Lee, 1986; Kosiak, 1961; Brand, 1976). During rowing, large pressures are applied to the buttocks in a cyclical fashion. During the drive phase of the stroke, the rower pulls on the oar handles, which begin to partially support the rower's body weight. This phase allows body-seat IP to be periodically reduced, which may permit periodic blood flow to the buttocks tissues (Koopman et al., 2009). Periodic blood recirculation can prevent the development of pressure-related injury in normal sitting (Koopman et al., 2009), however pressure injury to the buttocks is a common complaint among the aforementioned female rowers. The shear present in the buttocks tissues may be preventing blood recirculation.

During the recovery phase, the rower's upper body mass is mostly supported by the seat. The amount of pressure needed to cause vascular occlusion is halved when shear is present. Thus it is conceivable that some soft tissues of the buttocks remain ischemic throughout the rowing cycle, contributing to the likelihood of pressure injury (Bennett & Lee, 1986; Mathieu & Mani, 2007; Tam et al., 2003).

In order to reduce the likelihood of blisters and vascular occlusion resulting from the seat edge, both large IP and large IP gradients must be reduced. Friction must be present at the seat surface to some degree to keep the rower atop the seat; however, a more uniform pressure distribution around the seat edges would reduce the magnitude of the peak IP and reduce large pressure gradients.

Flat areas of the seats were rarely reported as uncomfortable (one trial). However when reported as uncomfortable, the pressure data on the flat area of the seat was below the threshold for injury. The area of the seat reported was in the mid-line between the ITs. This finding supports the notion of bicycle saddle studies that the perineum, located between the ITs, has a poor load toleranceand should not bear weight(Bressel et al., 2007;Bressel et al. 2010).

6.4 Practical significance and recommendations:

Within the context of rowing, internal shear, temperature, moisture, tissue deformation, and externally applied pressure are contributors that result from, and can be modified by, the rowing seat. Both deep and superficial discomfort can be mitigated by altering rowing seat design.

Current rowing seat designs attempt to support the rower's upper body mass, while accommodating the movement of the ITs and coccyx. However, it is difficult to evenly disperse pressure on any seating surface given these bony protuberances. Rowing is a dynamic activity where the nature of the body's interface with the seat is in constant flux. As a result, pressure is non-uniformly applied to the buttocks, posing a challenge in designing a rowing seat to evenly redistribute pressure throughout the rowing stroke.

Non-uniformly applied pressure may ultimately lead to both superficial and deep injury, and in some cases permanent deformation of tissues, as self-reported by the participants in this study. The findings of this study suggest that certain characteristics of the seat are undesirable for our participants.

Firstly, it is clear that edges are a source of discomfort, high IP, and large IP gradients. While the bony tissues have a greater load tolerance than soft tissues, the body-seat IPs during rowing are too large to be localised in a small area. Pressure redistribution away from the moving bony prominences may be requisite to improving comfort and minimising the risk of pressure injury. Changes in grade on the seat surface should be smoothly contoured to avoid localising large pressures along a crest.

Secondly, interrupted blood flow to the buttocks may be an issue that can be mitigated by altering the rowing seat. Both externally applied pressure and shear stress contribute to ischemia. Completely uninterrupted blood flow may not be possible given that friction is always present at the seat surface (and thus shear in skin) keeping the rower in contact with the seat. However, reducing the magnitude of the IP gradients by dispersing pressure across the seat may lessen the shear stress in the skin of the buttocks, thereby lessening the occluding effect of shear on the local vasculature.

Additionally, the implementation of holes appears to create a number of problems for the user. Holes provide a hard edge over which pressures localise, increasing the potential for large IP gradients. The use of circular holes also may not appropriately address the gliding motion of the ITs during hip flexion and extension, causing impact with the hole edges. A potential solution may be to implement grooves oriented in the direction of IT gliding as opposed to holes. Grooves may more appropriately accommodate the movement of the ITs.

Further, the participants reported that seat holes appear to be interfering with smooth movement of the gluteal muscles as the ITs press against the perimeter of the holes. Three participants reported using foam rubber pads over their seats, and one participant had filled in the holes of her personal seat. These efforts were in order to reduce discomfort caused by the holes and other crests, while providing support under the ITs (National Canadian Women's Rowing Team members, Personal communication, July 8, 2011). This suggests that the ITs need to be accommodated to in a manner that avoids impactful mechanical distortion of the soft tissue against bony prominences.In addition to implementing grooves to accommodate the ITs, a compressible material should be considered for the superior surface of the grooves over which the ITs glide. This may provide an appropriate means of supporting the ITs and allowing uninterrupted gliding of the hip extensors over the skeleton.

During the drive phase of the rowing stroke the buttocks remain atop the seat while the rower's torso moves relative the rowing seat in the positive-x direction (Pollock et al., 2009), and the pelvis and coccyx rotate around the y-axis in the positive direction. Current rowing seat designs attempt to avoid contact with the coccyx; however, repetitive impact of the coccyx against the seat is a common complaint from the participants. Five participants reported that the posterior edge of the seat prevented a full range of motion by imparting pressure to the coccyx. Participants also communicated that repetitive coccyx contact with the rowing seat is particularly painful, and the coccyx begins to bear the rower's mass if it is in contact with the seat.Pressures as high as 69.37N/cm^{2}were measured between the coccyx and seat.These findings suggest that seat design should attempt to support the rower's weightwithout loading the coccyx during the time when the torso moves posteriorly relative to the seat.

The interaction between the body and rowing seat is dynamic. Different areas of the rowing seat are subject to applied pressure from the buttocks at different times. A sturdy seat material is necessary to support the rower's mass and maintain balance. However, a material that yields under high loads to adjust to changes in pressure during different phases of the rowing stroke may be useful in achieving a more uniform IP distribution in high pressure areas of the seat.

Frictionis always present at the body-seat interface. Shear in the skin causing separation of dermal layers is the cause of superficial blisters (Sanders et al., 1995). Friction is necessary to keep the rower stableatop the seat; however,the outer edges of the seat are responsible for the formation of blisters. The incidence of blisters may be lessened by reducing pressure and shear along the outer perimeter of the seat. The use of a material with a low coefficient of friction around the outer edge of the seat may be useful in reducing the likelihood of blisters to the buttocks and upper thigh. If the negative effectson the tissues of the buttocks can be alleviated, we may be able to improve rowing seat comfort, allow ease of skeletal and muscle movement, reduce the risk of pressure-related tissue injury, and improve performance. However, the degree to which the findings of this study are applicable to other seating surfaces is limited.

Bicycle saddles are a similar seating challenge, where body weight must be supported by a small surface area. However, one of the principal concerns of bicycle saddle design is the maintenance of the health of tissues located between the ITs (Spears et al., 2003).

These tissues, such as the perineum, are easily compressed and have a lower load tolerance than the ITs. As a result, it is suggested that pressure is localised to the ITs (Spears et al., 2003). This concept does not appear to apply to rowing seats, as the nature

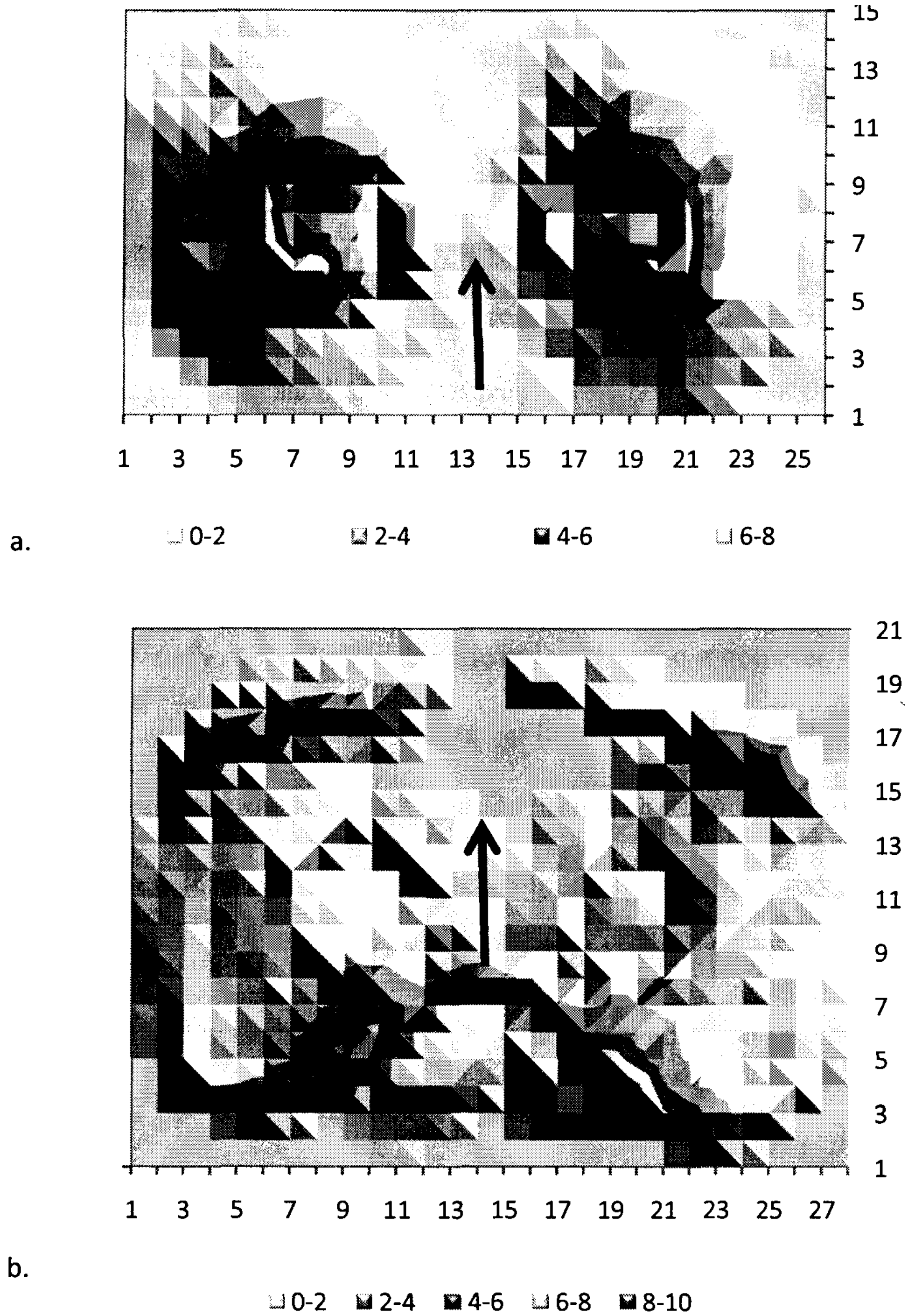

Figure 30XSensor body-seat IP map at the a. catch (15x26 sensels) and b. finish (21x27 sensels) positions. The area experiencing little pressure, indicated by an arrow, is the approximate location of the perineum. Pressure values are in units N/cm2. Maps are cropped to exclude pressure data below threshold.

of rowing movement is very different, the user's weight is largely supported by the buttocks, and the perineum appears to experience little pressure (Figure 30).

Further, the peak pressure reported in studies concerning bicycle saddles is 21.8N/cm^2 (Bressel et al., 2010), where as the peak body-seat IPs during rowing are over ten times this magnitude. For this reason, the findings of this study do not address the needs of bicycle saddle design.

Equestrian saddles are a more similar seating surface in that the loading is repetitive. To the best of our knowledge, there is no peer-reviewed data regarding the IP distribution between the rider and saddle. It is unclear as to whether or not the findings are applicable to equestrian saddles.

6.5 Assumptions & limitations:

The present study utilised an isokinetic indoor rowing ergometer as opposed to a racing boat. The study was performed indoors to limit the environmental effects on the interaction between the body and seat, including wind and the movement of the boat through water. However, the ecological validity of the study may be limited by differences in temperature and moisture indoors versus on the water. The ambient room temperature was not controlled, and may have had an effect of the participants' perspiration. Further, the absence of splashing water surrounding the participant may have also had an effect on moisture at the body-seat interface.

While a rowing boat was not used to exactly reproduce the environmental conditions of rowing on water, the ergometer correctly simulates the rowing form, and closely simulates the resistance at the handles of rowing on water (Nolte, 1987).

Inherent in pressure mapping is the requirement of placing a sensor between the interfacing surfaces. There are multiple limitations to using pressure mapping to evaluate the interaction between interfacing surfaces. Sensors placed between two surfaces may act as cushions, dispersing pressure. The XSensor mat may have acted as a cushion to some degree. Further, the rowing seat is a topographically non-uniform surface. The pressure mat, while flexible, does not perfectly conform to the interface between the seat and the body. The pressure sensors measure forces normal to their surfaces, but the forces exerted by the buttocks may not be perfectly normal to the seat surface. Thus, the forces measured may not have been acting in the measurement axis of the sensels and may be underrepresented. It was not possible to assess the directionality of the IPs. Further, the pressure sensors do not provide indications of tissue tolerance, shear, or friction (Titus &Polgar, 2009).

However, the XSensor mat data were used only qualitatively, as its purpose was to indicate areas of high pressure at the body-seat interface. The Tekscan sensor used in this study is extremely thin (0.1mm) and easily conforms to the surfaces in contact. Further, it is capable of detecting differences in pressure of 332N/cm^2 between sensing points spaced 1.27mm apart.

The position and movement the center of pressure could not be accurately calculated using the XSensor mat. During rowing, the peak pressures at the body seat interface exceeded the 10.34N/cm^2 upper sensing limit of the mat. The IPs measured during this study exceeded 20 times this saturation limit. Using data from saturated sensels would grossly under represent the pressures in those areas, and lead to an erroneous center of pressure.

Further, the pressure sensing devices available to the investigators were not capable of measuring shear at the body-seat interface. It is also not possible to measure shearstresses among and within internal tissues. In the present study, discussions regarding shear stresses are inferences made given the non-uniform distribution of pressure at the body-seat interface (Bennett and Lee, 1986). Further, discussions pertaining to changes in IP distribution under the ITs are inferences made upon the assumed movement of the pelvis (Pollock et al., 2009) during our study which may not match the pelvic movement in previous rowing studies. The exact anthropometry of the ITs in our participants was not measured.

Body-seat pressure mapping does not directly measure the IP between the body and seat. The interaction between the body and seat is affected by the participant's clothing.Clothing may influence factors involved in pressure injury such as friction and pressure dispersion. All participants wore their usual spandex rowing shorts for this study. The thin spandex material may have acted as a cushion, dispersing pressure to some degree. However, spandex shorts and unisuits are commonly worn during rowing, and were worn during testing to accurately recreate the interaction between the buttocks and the seat.

Another factor influencing the body-seat IP distribution is the differences in soft tissue thicknesses and distribution in the buttocks and upper thigh between subjects. Thus, the pressure dispersive capabilities of the soft tissues in the buttocks may vary across individual participants.

The use of a subjective discomfort scale raises an issue of transferability, as the perception of discomfort may vary among individuals both within and out of the study. However, the strength of the GDA is that it is quantitativeand has been previously shown to be stable, reliable,and sensitive to changes over time in a wheelchair studies(Crane et al., 2004; Crane et al., 2005) where pelvic tilt and trunk flexion and extension are involved (Hobson &Tooms, 1992).

Additionally, the seats were not randomised. Participants could not be blind to which seat they were using during each phase of testing. In order to appropriately position themselves on the rowing seat, the participant must touch the rowing seat. An experienced rower is able to keenly identify which seat they are using given only tactile feedback from the buttocks. Knowledge of using a seat previously perceived as comfortable or uncomfortable may have influenced the discomfort scores reported.

The TAWC has been previously validated for use in wheelchair seating discomfort. Wheelchair propulsion is similar to rowing in that there is a pelvic tilt concomitant to propulsive movements. In light of this, this questionnaire was used in the present study. The GDA section of the TAWC is used in this study however it has not been validated for use in rowing.

The participants used in this study were not randomly selected. The elite female rowers participating in this study were able to execute highly consistent, proper rowing form. This is confirmed by the small variability of pressures seen between rowing strokes (Figure 17). A less experienced rower may have less ideal interactions with the rowing seat. The degree to which amateur or male rowers exhibit pelvic tilt and move upper body center of gravity over the seat would require more investigation. The anatomy of an average male pelvis, and thus the distance between inferior surfaces of the ITs, is likely different than that of an average female. The findings of this study may not pertain to male or amateur rowers, but provide insight to the body-seat interface using a demographic of rowers who self-reported various complaints regarding rowing seats.

Further, the findings of this study indicate that large changes in pressure over distances as small as 1.27mm exist at the body-seat interface. This finding agrees with Bressel and Cronin (2005) in that high spatial resolution sensors are needed for body-seat-IP mapping applications on surfaces with well-defined edges.

Lastly, the orientation of the Tekscan sensors attached to the seats was not fixed to a coordinate system. Alignment of the pressure sensors would permit the calculation of IP gradient direction. Calculating the direction of IP gradients throughout the rowing stroke would be useful in characterising the dynamic interaction between body-seat IP and the inferred movement of the ITs.

6.6 Conclusion:

In conclusion, weakly positive relationships exist between peak IP and discomfort, and between maximal IP gradient and discomfort. 20% of the discomfort arising from the rowing seat is attributable to the maximal IP gradient between the seat and the buttocks, and 18% of the discomfort is attributable to the peak IP. However, several suggestions can be made regarding the design of the rowing seat.

The findings of this study do not support the notion of concentrating body-seat IP under the ITs. The large magnitude of the IPs measured exceeds those associated with discomfort and injury. Achieving a uniform IP distribution between the buttocks and the rowing seat is a challenge. However, dispersing pressure and minimising the magnitude of IP gradients may minimise discomfort and the risk of pressure-related tissue injury.

Our findings cumulatively suggest that seat topography and hardness are major factors in rowing seat discomfort that may be modified in order to disperse pressure. Edges should be avoided on body-seat contact areas. Flat or smoothly contoured areas were rarely reported as uncomfortable; however,prominent crests were often reported as sources of discomfort. Additionally, the implementation of holes to accommodate the movement of the ITs during hip flexion and extension is inappropriate. The use of non-circular grooves oriented in the x-axis may effectively accommodate the IT gliding path.

Multiple materials should be considered to address a number of issues at different locations of the seat surface. Soft materials should be considered for the areas under the IT gliding path; materials with low coefficients of friction should be considered for areas causative of blisters, and a passively dynamic material should be considered for the rest of the seat surface.

Future studies concerning the body-seat IP distribution during rowing would benefit from kinematically tracking the seat movement and the participants' pelvic tilt and center of mass in order to accurately identify problematic phases of the rowing stroke. Alternatively, MRI has been used to image compression of soft tissues under the ITs (Bressel et al., 2007). This technology would be useful to image the interaction between bony and soft tissues in the buttocks during rowing.

Additionally, aligning the pressure sensors in a consistent orientation regardless of position on the seat surface would permit the calculation of IP gradient direction. Also, large changes in IP occur over small distances (Figure 20;Figure 29), necessitating the use of high spatial resolution pressure sensors for this application. Lastly, a minimum sample size of 36 should be used to achieve a statistical power of 0.8.

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Appendices

Appendix A: Discomfort Survey

Participant survey

You will be given one survey package for each seat used in this study. Contained within each package are a photograph of the seat used in your trial, and a questionnaire regarding your experience with the seat.

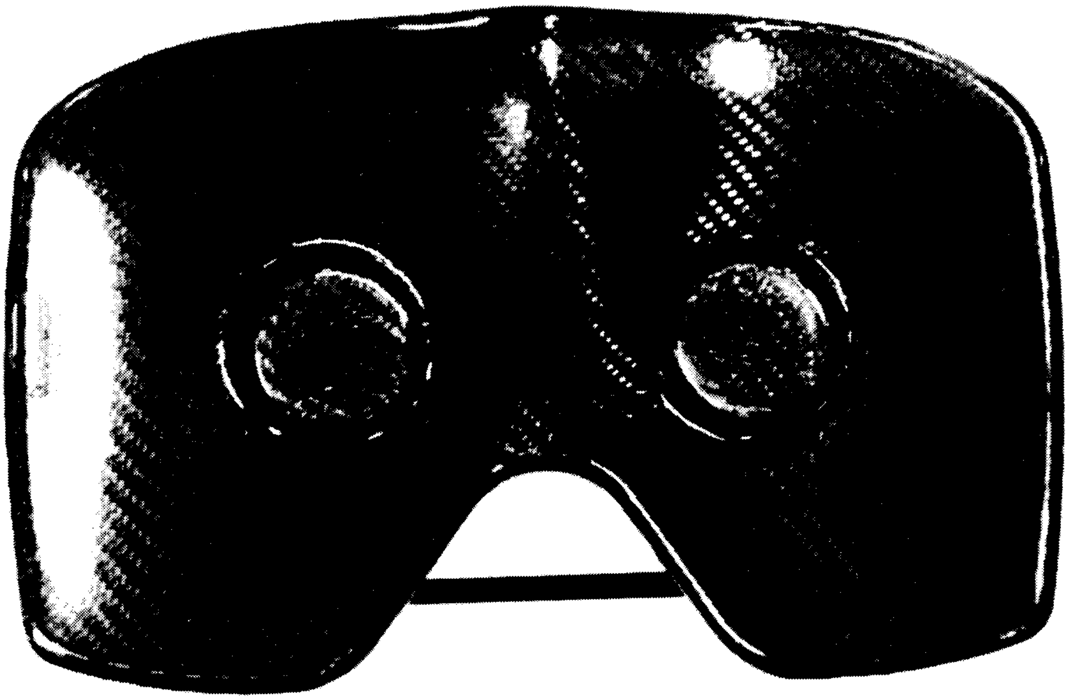
Instructions:

1. On the photograph, please circle or shade in the area(s) of the seat that you find to be uncomfortable. If you do not find any areas to be uncomfortable, please do not shade in any part of the photograph.
2. If you experience discomfort from the seat, please fill out the questionnaire. Please place a checkmark clearly within the appropriate boxes. Please do not place checkmarks in between boxes.

Date: ________________

Time: ________________

Participant number: ______________



1

Seat # ______________________

Participant code ______________

Date _______________________

General Discomfort Assessment

Please rate your answer on the following scale: (place a mark in the appropriate box)	Strongly disagree	Disagree	Partly disagree	Neither agree nor disagree	Partly agree	Agree	Strongly agree
While seated …							
…I feel poorly positioned							
…I feel like I have been in one position for too long							
…I feel like I need to move or shift my position							
…I feel aches, stiffness, or soreness							
…I feel pressure in some part or parts of my body							
…I feel too hot or cold or damp							
…I seek distraction to relieve discomfort							
…I feel uncomfortable							
…I feel no pain							
…I feel stable (not sliding or falling)							
…I feel comfortable							
…I feel good							
…I feel able to concentrate on my activities							

Tool for Assessing Wheelchair disComfort (TAWC) – Scoring Key for GDA Score (total all item scores)

Part II: General Discomfort Assessment

Please rate your answer on the following scale: (place a mark in the appropriate box)	Strongly disagree	Disagree	Partly disagree	Neither agree nor disagree	Partly agree	Agree	Strongly agree
While seated in my wheelchair…							
…I feel poorly positioned	1	2	3	4	5	6	7
…I feel like I have been in one position for too long	1	2	3	4	5	6	7
…I feel like I need to move or shift my position	1	2	3	4	5	6	7
…I feel aches, stiffness, or soreness	1	2	3	4	5	6	7
…I feel pressure in some part or parts of my body	1	2	3	4	5	6	7
…I feel too hot or cold or damp	1	2	3	4	5	6	7
…I seek distraction to relieve discomfort	1	2	3	4	5	6	7
…I feel uncomfortable	1	2	3	4	5	6	7
…I feel no pain	7	6	5	4	3	2	1
…I feel stable (not sliding or falling)	7	6	5	4	3	2	1
…I feel comfortable	7	6	5	4	3	2	1
…I feel good	7	6	5	4	3	2	1
…I feel able to concentrate on my work or activities	7	6	5	4	3	2	1

AppendixB: Consent Form

Consent Form

Body-Seat Interface Pressure and Discomfort in Rowing

Researchers:

Role:		**Principal investigator**	**Study investigator**
Name:		Volker Nolte	Michael Navy
Title & Position:		Assistant professor (supervisor)	Masters Candidate (student)
Degrees:		PhD Biomechanics	Hon. B.Sc. Kinesiology
Department:		Kinesiology	Kinesiology
Mailing address:	**Building & Street Address**	2142 Thames Hall University of Western Ontario	
	City, Province	London, Ontario	
	Postal Code	N6A 3K7	
	Telephone	[redacted]	[redacted]
	Email	[redacted]	[redacted]

You are invited to take part in a study investigating the pressures involved at the interface between the body and the rowing seat. It is important for you to understand why this study is being performed and what it will involve. Please take your time to read and thoroughly understand all of the information provided. Please feel free to ask any questions if any information is unclear.

The purpose of this study is to determine what characteristics of rowing seats are desirable and which are not. Currently, the study is focused on female rowers, as rowing seat fit is often less ideal among females. This study will include a maximum of two sessions lasting, at most, approximately two hours per participant.

The study is recruiting exclusively from the Canadian National Women's Rowing team. You are eligible to participate in this study if you are a team member between the ages of 18 and 49 and have competed, or have been selected to compete, at the national level.

The testing will take place outside of practice time. If you are unable to attend the designated testing date, please inform the study investigators immediately and an alternate date will be arranged. This study will take place at the UG Biomechanics Research Lab at the University of Western Ontario (Thames Hall building, room 2125).

If you choose to participate, pressure measurements will be taken between the seat and the buttocks and upper thighs while rowing. The study investigators will be looking for potentially problematic pressure distribution patterns. Pressure measures will be obtained via the use of a pressure sensing mat placed between the body and seat.

If you decide to take part in this study, you will be required to perform a standard training warm-up, determined by your usual regimen. You will then be required to perform several rowing trials on a rowing ergometer. The rowing trials will be of short-duration, using six seat designs, and will be conducted at an endurance pace (20 strokes per minute). You will begin rowing on the ergometer until a consistent form, power, and stroke rate is achieved, at which time the pressure recording will begin and continue for several full rowing strokes. After each test, you will be required to fill out a questionnaire regarding your experience during the rowing trials. The questionnaire will report on the presence or absence of discomfort experienced while rowing on the seat. If and only if discomfort is present, then the nature and degree of discomfort experienced is assessed, and you will be required to identify areas of discomfort on two-dimensional diagrams of the buttocks, and the rowing seat.

Given the mild nature of the tests, you should not experience any unusual discomfort as a result of the rowing trials though you may experience discomfort characteristic of normal training. Additionally, you may experience discomfort to the buttocks during the study, as different rowing seat designs will be used that you may not be accustomed to. Further, you should not experience any training effects as a result of the study. The study investigators do not expect the study to interfere considerably with your training regimen.

Should you feel any unusual discomfort during the study, you may stop the exercise and notify the Study Investigator immediately. You may stop the exercise at any time. An alternate day and time will be arranged if you wish to retry the trials.

The investigation team proposes that you do not participate in extra sports or extracurricular activities (extra workouts, lifting masss, etc.) on the day of testing (aside from your regular training regimen) in order to avoid influencing your rowing form. If you feel sore, injured, or ill in any way on a day of testing, then you should not participate on that day (an alternate testing day will be arranged). If you feel that you have sensory deficits to the buttocks or upper thighs, please do not participate in this study. If you are experiencing any of the following problems at the start of the study, including any condition limiting anterior and posterior pelvic tilt; hip, spine, knee, or ankle flexion and extension, please do not participate in this study.

You will not receive any immediate personal performance benefit from participating in this study, however you will be provided with information regarding your interaction with the rowing seat. Your participation may help us attain new knowledge that may later benefit you or future rowing athletes.

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time without any affect on your team status. You may be asked to reschedule your testing slot for any of the following reasons:

- If you experience unusual discomfort performing any of the required tests
- If you are experiencing a transient illness or injury
- If you are unable to attend during the scheduled study trials

All data collected from the study will be used for research purposes only, and kept completely confidential. Neither your name, nor any information that could identify you, will be made available to any persons except for the Principal Investigator and Study Investigator. If the results from this study are published or presented, your name will not be used. Data and personal information will be kept separately, and the files containing them will be password protected. No paper records containing personal identifiers will be kept, and all personal information will be deleted three months after study completion.

If you have any questions about your rights , please contact the Office of Research Ethics at 519-661-3036, or by email at ethics@uwo.ca. Representatives of The University of Western Ontario Health Sciences Research Ethics Board may contact you or require access to your study-related records to monitor the conduct of the research.

CONSENT FORM

Body-Seat Interface Pressure and Discomfort in Rowing

Investigators: Dr. Volker Nolte, Michael Navy.

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

You will be given a copy of this letter of information and consent form once it has been signed. You do not waive any legal rights by signing the consent form.

Participant:

Name (printed): ______________________________

Signature: ___________________________________ Date: ____________________

Person obtaining informed consent:

Name (printed): ______________________________

Signature: ___________________________________ Date: ____________________