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Development of a Dynamic Biomechanical Model for Load Carriage: Phase IV Part C1

Assessment of Pressure Measurement Systems on Flat Surfaces for use in Human Load Carriage

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Abstract

A variety of pressures mapping technologies have been used to assess contact pressures between human tissues and solid flat surface materials. However, research on the accuracy, repeatability, and creep for these technologies is limited. Three commonly used technologies were evaluated for accuracy, repeatability, and creep on a flat surface under highly controlled laboratory conditions. The systems tested included a resistive ink technology known as the F-scan F-socket (Tekscan Incorporated), a piezoresistive technology known as the FSA seat mat (Vista Medical, Limited), and a capacitance technology known as the XSENSOR® seat mat (XSENSOR® Technology Corporation). Loads between 9.392 kg and 19.627 kg were placed on each sensor using three standardized protocols: an incremental, a low threshold and a creep protocol. For overall accuracy during incremental loading, FSA mat measured a pressure that was 74.5% of the actual applied pressure, the F-scan measured a pressure that was 247.0% of the actual applied pressure and the XSENSOR® measured a pressure that was 75.1% of the actual applied pressure. The overall accuracy for low threshold testing, found that the FSA mat measured a pressure which was 181.0% of the actual applied light pressure, the F-scan measured a pressure which was 292.0% of the actual applied light pressure and the XSENSOR® measured a pressure that was 103% of the actual applied light pressure. Creep characteristics as a percentage were found to be 19.54% for the FSA mat, 17.23 % for the F-Scan, and 17.62 % for the XSENSOR®. No pattern of repeatability was found. In summary, the XSENSOR® and FSA pressure measurement systems were superior to the F-Scan system in terms of accuracy, although the XSENSOR® was more accurate than the other two systems at low threshold pressures. The main drawback of each system at this time is the long settling time needed to get more accurate data due to creep. This needs to be corrected within the software of each system. For use in human load carriage, there will need to be adjustments in amplitude and creep characteristics.

Résumé

Une variété de technologies ont été utilisées pour le mappage des pressions de contact entre les tissus humains et des matériaux à surface plane solide. Toutefois, les études de ces technologies pour connaître leur justesse, la répétabilité et le fluage sont limitées. Trois technologies courantes ont été évaluées en laboratoire, dans des conditions très contrôlées, pour déterminer la justesse, la répétabilité et le fluage sur une surface plane. Les systèmes mis à l'essai comprenaient un système à pâte résistive, soit le système F-scan F-socket (de Tekscan inc.), un système piézorésistif, soit le coussin FSA (de Vista Medical ltée) et un système capacitif appelé coussin Xsensor (de Xsensor Technology Corporation). Des charges de 9,392 kg et de 19,627 kg ont été placées sur chaque capteur selon trois protocoles normalisés : incrémental, à faible seuil et de fluage. En termes de justesse globale durant l'application incrémentale de charge, la pression mesurée par le coussin FSA correspondait à 74,5 % de la pression réelle appliquée; la pression mesurée par le F-Scan était de 247,0 % de la pression réelle appliquée; et la pression mesurée avec le Xsensor représentait 75,1 %. Les essais du faible seuil avec les différents systèmes ont donné les résultats suivants : la justesse était de 181,0 % de la faible pression appliquée avec le coussin FSA, de 292,0 % avec le F-Scan et de 103 % avec le système Xsensor. En pourcentage, les caractéristiques de fluage s'expriment comme suit : 19,54 % avec le coussin FSA, 17,23 % avec le F-Scan et 17,62 % avec le système Xsensor. Aucune tendance n'a été observée en ce qui a trait à la répétabilité. En résumé, les systèmes de mesure de pression Xsensor et FSA se sont avérés supérieurs au système F-Scan sur le plan de la justesse, bien que le système Xsensor soit plus précis que les deux autres systèmes lors des mesures prises avec des pressions faibles. Le principal inconvénient de chacun des systèmes est le long délai de stabilisation nécessaire pour obtenir des données plus exactes, en raison du fluage. Ce problème devra être corrigé dans les logiciels fournis avec chaque système. Pour pouvoir utiliser ces systèmes pour le transport de charge par les humains, des modifications devront être apportées à l'amplitude et aux caractéristiques de fluage.

Executive Summary

Research to study the effects of contact pressure as a result of backpack load is vital since excessive, uncomfortable pressure due to heavy backpack loads; may lead to premature fatigue or injury, may limit solider mobility, and can impair fighting ability. To better understand how backpack pressure affects comfort and performance; standardized, accurate and reliable equipment is needed to measure the contact pressures experienced by soldiers. Currently, safety standards for skin contact pressure have not been identified in the literature, nor has suitable pressure-sensing equipment, which can accurately and reliably measure contact pressure.

The purpose of this report is to begin the process of analysing different pressure measurement systems for possible use in determining acceptable skin tolerance pressures during load carriage. Since numerous pressure measurement technologies have been developed in recent years, it is time to conduct a thorough review of such systems. The purpose of this study was to compare three types of systems on a flat surface for evaluation of their validity and reliability, their accuracy at the threshold level and their creep characteristics.

Methods

The three pressure technologies tested included: a resistive ink technology by Tekscan Inc., (F-scan F-socket model); a capacitance technology by XSENSOR® Technology Corporation (X2 seat system); and a piezoresistive technology by Vista Medical Ltd., (Medical seat UT model). Each pressure pad was places on a 3 mm Bocklite® cushion and marked by the researcher to ensure that the loads were placed on the same part of each pressure pad to maintain testing consistency.

Three protocols were performed in a randomized order. An incremental protocol was used to test accuracy and repeatability by placing loads between 9.392 kg to 19.627 kg on each pad for 2 minute intervals. Each loaded interval was followed by a 2 minute unloaded condition before the next load was placed on the pad. A low threshold protocol was used to test light load accuracy by placing it on a predetermined place on the pad for 20 minutes. The load created a light pressure that was 1 unit of pressure above the manufacturer's lowest recommended threshold. A creep protocol was used to study the creep characteristics as a result of placing an 18.627 kg load on each pad for 58.8 minutes. All data were collected at 1 sample/ second and normalized by dividing the measured pressure gathered using the pressure system by the actual applied pressure to allow comparison between systems.

Results and Discussion

For overall accuracy during incremental loading, the FSA mat measured a pressure that was 74.5% of the actual applied pressure, the F-scan measured a pressure that was 247.0% of the actual applied pressure and the XSENSOR® measured a pressure that was 75.1% of the actual applied pressure. No pattern of repeatability was found when test-retest conditions were compared. The overall accuracy for low threshold testing showed that the FSA mat measured a pressure which was 181.0% of the actual applied pressure, the F-scan measured a pressure which was 292.0% of the actual applied pressure and the XSENSOR® measured a pressure that was 103% of the actual applied pressure. These results suggest that neither system was within the acceptable range of accuracy except for the XSENSOR® at light pressure thresholds and that all systems need to be improved to be scientifically repeatable. The creep characteristics were found to be 19.54% for the FSA mat, 17.23% for the F-Scan, and 17.62% for the XSENSOR®, which suggests that all systems need corrections in either the software or the hardware to reduce creep.

Conclusions

In summary, the XSENSOR® and FSA pressure measurement systems were superior to the F-Scan system in terms of accuracy, however the XSENSOR® was more accurate at light pressures. The main drawback of each system at this time is the long settling time needed to get more accurate data due to creep and the lack of repeatability. The lack of acceptable repeatability means that measures should be repeated at least five times to provide confidence in the results. For use in human load carriage, there will need to be adjustments in amplitude and creep characteristics

Sommaire

Les études sur les effets de la pression de contact produite par une charge d'un sac à dos sont essentielles, étant donné qu'une pression excessive et inconfortable exercée par un sac à dos lourd peut causer de la fatigue prématurée ou des blessures, limiter la mobilité des soldats et amenuiser leur capacité de combat. Afin de mieux comprendre les effets de la pression d'un sac à dos sur le confort et la performance, il faut avoir accès à de l'équipement normalisé, exact et fiable pour mesurer les pressions de contact subies par les soldats. À l'heure actuelle, la documentation ne mentionne pas les normes de sécurité relatives à la pression de contact, ni l'équipement de détection de pression qui permet de mesurer avec exactitude et fiabilité la pression de contact.

Le présent rapport vise à lancer le processus d'analyse de différents systèmes de mesure de pression qui pourraient être utilisés pour établir les valeurs de tolérance de la peau aux pressions durant le transport d'une charge. Étant donné que bon nombre de systèmes de mesure de la pression ont été mis au point au cours des dernières années, il est temps d'examiner ces systèmes en profondeur. L'étude a pour but de comparer trois types de systèmes sur une surface plane afin d'évaluer leur validité et leur fiabilité, leur justesse à la valeur seuil et leurs caractéristiques de fluage.

Méthodes

Les trois technologies de mesure de pression mises à l'essai comprenaient : un système à pâte résistive fabriqué par Tekscan Inc. (modèle F-scan F-socket); un système capacitif de Xsensor Technology Corporation (coussin X2) et un système piézorésistif conçu par Vista Medical Ltd. (coussin de modèle médical UT). Chaque coussin a été placé sur un coussin Bocklite® de 3 mm et marqué par le chercheur pour que les charges soient placées au même endroit sur chaque coussin pour garantir la cohérence des essais.

Trois protocoles ont été suivis selon un ordre aléatoire. Le protocole incrémental a été utilisé pour tester la justesse et la répétabilité; des charges variant de 9,392 kg à 19,627 kg étaient placées sur le coussin pendant 2 minutes. Chaque période de deux minutes étaient suivie d'une période de deux minutes sans charge, avant le dépôt de la prochaine charge sur le coussin. Le protocole à faible seuil a été utilisé pour tester la justesse des systèmes avec une charge légère; une charge légère était placée à un endroit déterminé sur le coussin pendant 20 minutes. La charge produisait une pression légère correspondant à une unité de pression de plus que le seuil minimal recommandé par le fabricant. Un protocole de fluage a été suivi pour étudier les caractéristiques de fluage résultant de l'application d'une charge de 18,627 kg sur chacun des coussins pendant 58,8 minutes. La collecte de toutes les données a été effectuée au taux d'un échantillon par seconde, et les résultats ont été normalisés en divisant la pression mesurée au moyen du système de pression par la pression réelle appliquée, afin de permettre la comparaison des systèmes.

Résultats et analyse

En termes de justesse durant l'application incrémentale de charges, la pression mesurée par le coussin FSA correspondait à 74,5 % de la pression réelle appliquée; la pression mesurée par le F-Scan était de 247,0 % de la pression réelle appliquée; et la pression mesurée avec le Xsensor représentait 75,1 %. Aucune tendance n'a été observée en ce qui a trait à la répétabilité lors de la comparaison des résultats d'un essai à l'autre. Les essais à faible seuil avec les différents systèmes ont donné les résultats suivants : la justesse était de 181,0 % de la faible pression appliquée avec le coussin FSA, de 292,0 % avec le F-Scan et de 103 % avec le système Xsensor. Les résultats obtenus montrent que la justesse d'aucun des systèmes ne se situe dans la plage acceptable, sauf le système Xsensor lors des essais à faible seuil, et que tous ces systèmes doivent être améliorés pour donner des résultats scientifiquement répétables. Les caractéristiques de fluage s'expriment comme suit : 19,54 % avec le coussin FSA, 17,23 % avec le F-Scan et 17,62 % avec le système Xsensor, ce qui laisse croire que tous les systèmes nécessitent des corrections, soit au niveau du matériel, soit au niveau du logiciel, pour réduire le fluage.

Conclusions

En résumé, les systèmes de mesure de pression Xsensor et FSA se sont avérés supérieurs au système F-Scan pour ce qui est de la justesse, bien que le système Xsensor soit plus précis pour des mesures prises avec des pressions faibles. Le principal inconvénient de chacun des systèmes est le long délai de stabilisation nécessaire pour obtenir des données plus exactes, en raison du fluage et de l'absence de répétabilité. Cette lacune au niveau de la répétabilité signifie que les mesures doivent être prises au moins cinq fois pour que les résultats soient fiables. Pour pouvoir utiliser ces systèmes pour le transport de charge par les humains, des modifications devront être apportées à l'amplitude et aux caractéristiques de fluage.

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1.0 Introduction

Anytime the human body comes in contact with another object, compressive forces are applied to the skin to transfer the load to the skeleton. Regardless of how the external forces are applied, the skin undergoes varying degrees of deformation resulting in stress to the underlying tissue. These external forces are often described in terms of force per unit of area or pressure. When repetition, duration and/or level of pressure on the skin are too great, tissue damage may occur. For soldiers, pressure to the tissues can occur as a result of supporting and transporting backpack loads, particularly on tissues located under the shoulder strap and waist belt. Given constraints of various missions and increased reliance on technology, it is critical for modern combat or peacekeeping forces to move their own loads by foot using personal load carriage systems (PLCS) which includes backpacks.

Research to study the effects of contact pressure, as a result of backpack load is vital since excessive, uncomfortable pressure due to heavy backpack loads; may lead to premature fatigue or injury, may limit solider mobility, and can impair fighting ability. To better understand how backpack pressure affects comfort and performance; standardized, accurate and reliable equipment is needed to measure the contact pressures experienced by soldiers. Currently, safety standards for skin contact pressure have not been identified in the literature, nor has suitable pressure-sensing equipment which can accurately and reliably measure contact pressure.

The purpose of this report is to begin the process of analysing different pressure measurement systems for possible use in determining acceptable skin tolerance pressures during load carriage. The current system used by the Ergonomics Research Groups at Queen's University is the Tekscan F-scan system. In previous reports, we have attempted to place these sensors directly on the skin without success since they are not conducive to differences in surface compliance (Morin et al., 1998). Since numerous pressure measurement technologies have been developed in recent years, it was decided to conduct a thorough review of such systems. The purpose of this study was to compare three types of systems on a flat surface to evaluate their validity and reliability, their accuracy at the threshold level and their creep characteristics. The report entitled "Assessment of Pressure Measurement Systems on Curved Surfaces for use in Human Load Carriage" (Fergenbaum et al., 2003) was written to compare the effectiveness of pressure measurement systems on curved surfaces that represent the shoulder and waist cylindrical and elliptical surfaces respectively. The final report in the series entitled "Dynamic Assessment of Pressure Measurement for use in Human Load Carriage" (Fergenbaum et al., 2003) was written to get a sense of which systems might be most useful in on-body dynamic conditions. Some of these findings were also reported in gait studies (Morin et al., 2003) where they were used as insoles to measure ground reaction forces.

2.0 Review of Literature

A number of commercial systems are available to measure contact pressures. These systems are based on a number of different technologies, including: resistive ink technology (Tekscan, Inc.[1]), capacitance-based technology (XSENSOR® Technology Corp.[2] or Novel Electronics Inc.[3]), and piezoresistive technology (Vista Medical, Inc[4]).

Past scientific studies investigating pressure technology are contradictory. F-Scan®, manufactured by Tekscan, Inc., has by far received the most attention in the scientific literature. This company developed a relatively simple resistive ink pressure technology, known as the F-Scan (F-socket) series. Initial studies involving F-scan were positive. For instance, Fuller (1995) found that when F-scan insole sensors were used under a test-retest condition, the location of bony landmarks, varied by as little as approximately 10%. Additionally, Gorton et al. (1996) compared use of the F-Scan system with a conventional force platform in paediatric patients and found that pressure data obtained with the F-Scan were within 10% of the values obtained with a force platform. In addition, Ahroni et al. (1998) assessed the reliability of the F-scan insole shoe system under test-retest conditions, and reported low to good reliability for peak pressures (Intraclass correlation from 0.493 to 0.832) and acceptable coefficients of variation, ranging from 0.116 to 0.240. As well, Ferguson-Pell and Cardi (1991) reported that tests of the Tekscan Clinseat® (comprised of 2056 sensing elements) showed a mild 15% creep and a hysteresis value of ± 20%.

Despite the initial popularity of the F-Scan, conflicting reports have since emerged concerning the performance capabilities of the Tekscan resistive ink technology. Early concerns regarding the accuracy and repeatability of the F-Scan system began to appear in the published literature in the early 1990's (Cavanagh et al., 1992; McPoil et al., 1995) and have continued to accumulate. More recent studies report errors in accuracy to be as high as 62%, even under conditions of controlled mechanical loading (Hadcock, 2002, Luo et al., 1998; Sumiya et al. 1998)

Studies commissioned separately by both the Canadian and United States military have also raised concerns about the F-Scan system as a measurement tool for contact pressures. For example, a report for the U.S. Army Medical Research and Material Command (Sih, 2001) concluded that the creep behaviour of the loaded F-Scan sensels caused calibration errors that contributed to total load error exceeding 30% during walking and running trials. Further, a U.S. Army Institute of Environmental Medicine (USARIEM) report (Harman, et al., 1999) concluded that F-Scan produced unacceptable errors for a military footwear study (37% ± 29% error at 3 selected points during the walking cycle), when F-scan was compared to force platform data. In addition, a Canadian Defence Research and Development Canada (DRDC) study (Morin et al., 2001) reported problems with the F-Scan system. The study examined the effects of compliance and changes in system hardware for the F-Scan systems and found that these factors could cause differences in output between 5-32%.

More recently, Smith et al. (2002) compared the F-scan insole sensor to the VICON motion system (Oxford Metrics, U.K.) for accuracy of the timing of detection of pressure. Results showed poor detection accuracy given that the F-scan detected events ranging from + 35ms (detected a gait event before it actually happened) to -55ms (recognized a gait event after it happened). In terms of reliability of steps taken during gait, Smith et al. (2002) reported a 5.5% detection error in which the F-Scan system missed events completely. Of these detection errors, 80% were due to failure of the force sensing array signal to reach the programmed threshold. In addition, usage of a sensor for more than 50 steps was also a confounding factor causing the F-Scan to lose accuracy (Woodburn & Helliwell, 1996).

Calibration of Tekscan equipment has also been raised as a concern in research. For example, Lu and Lin (1996) reported that contact time, contact area, the amount of force applied on the pressure mat at the time of calibration and measurement, the consistency of contact time before calibration and measurement, and the time between calibration and measurement all significantly affected the accuracy of measurement using the Tekscan seat pressure measurement system. A recent study designed to measure the pressure interface of prosthetic limbs for flat and curved prosthetic moulds (Polliack et al. 2000), showed that the Tekscan F-socket system performed poorly giving 8% (flat) and 11% (curved mould) accuracy error; a 42% (flat) and a 24% (curved mould) hysteresis error, and a 12% (flat) and a 33% (curved mould) drift error. Given the concerns of resistive ink technology in terms of accuracy (errors ranging from 5.5% to 63%), reliability (correlations ranging from 0.493 to 0.832), creep characteristics (15%), hysteresis characteristics (20%), and calibrations procedural concerns; it is clear that other pressure-sensing technologies should be investigated

Although research is scarce, some published studies have examined the performance of capacitance-based pressure measurement systems. In an early study, Rash et al (1997) compared the accuracy and repeatability of a capacitance-based system known as Pedar (Novel Electronics, Inc.) to the F-Scan® (Tekscan, Inc.) insole shoe system. They compared actual predicted pressures to the pressures measured by each system and found Pedar to have the slightly greater accuracy (mean error for Pedar = 2.0%; mean error for F-Scan=3.1%) and slightly better repeatability (standard deviation for Pedar = 1.1%; standard deviation for F-Scan = 3.6%). It should be emphasized that these slight differences were not significantly different suggesting both the Pedar and F-scan performed similarly. More recently, Hsiao et al (2002) compared the Pedar Y-sized right insole to the F-scan insole trimmed to Pedar size. The Pedar system showed the greatest accuracy in the manufacturers recommended range (50-500Kpa) with a measurement error for the Pedar in the range of -0.6 to 2.7%. In contrast, the F-scan demonstrated a measurement error in the range of 1.3 to 5.8 %. As well, Hsiao et al (2002) showed that measurement errors increased, in the range of -26.3 to 33.9% when pressures were applied outside of the manufacturers recommended range. Recently, studies of another new capacitance-based system known as the XSENSOR®® have begun to appear in the scientific literature (Yuen and Garrett, 2001; Shechtman et al., 2001). However, these

authors did not test the performance characteristics for the XSENSOR®, such as accuracy or repeatability, since these publications were clinical in nature.

Research is also limited on the performance characteristics of piezoresistive pressure measurement systems. Of the published studies, one by Ferguson-Pell and Cardi (1991) compared the piezoresistive VERG Force Sensing Array by Vista Medical, Inc., to the Tekscan Clinseat® system and reported hysteresis values of ± 10% (VERG) and ± 20% (Tekscan) and creep characteristics of + 4.6% (VERG) and + 15 % (Tekscan). In a poorly designed preliminary study, Jeffcott et al (1999) examined the effects of incorrectly fitted saddles on horses using a 40cm by 40 cm piezoresistive Force Sensing Array by Vista Medical, Inc. Jeffcott et al (1999), concluded that the piezoresisitive technology provided an accurate and reliable measure of pressure applied to horses' backs; however, weaknesses in methodology and unrelated results do not support these conclusions.

Based on a review of the current literature, there is a clear need to conduct objective, well-controlled studies to evaluate overall performance characteristics of modern pressure measurement instruments.

3.0 Purpose

The goal of this research is to evaluate the latest pressure-sensing technologies using standardized flat surface tests, to evaluate their validity and reliability over a number of loads and to examine their minimum threshold and creep characteristics. In total, three systems were evaluated for possible use in future human load carriage trials.

4.0 Methodology

The pressure sensing systems tested included a resistive ink-based sensor by Tekscan, Inc., a piezoresistive-based sensor by Vista Medical, Ltd., and a capacitance-based sensor by XSENSOR® Technology Corp. All systems tested had visual computer displays to allow the user to view data in graphical or colour-coded formats during data collection. As well, all systems had capabilities to allow the user to export to a spreadsheet file for further analysis.

The resistive ink technology tested was the F-Scan (F-socket series) model, manufactured by Tekscan Incorporated. It is constructed of a thin (0.18 mm thick) flexible, trimmable, printed ink circuit which was detachable from the electronics. The software tested was version 4.21 with an associated 9811 sensor pad. The sensing region dimensions of the sensor tested measured 20.3 cm by 7.6 cm and comprised of 96 individual sensels. The sensors tested had a scan rate of 208 frames per second. The manufacturer recommended an operating range is between 0 - 241.3 kPa (0-35 PSI). The system was newly calibrated in the laboratory using a calibration device sold by the manufacturer.

The capacitance technology tested was the X2 seat system, manufactured by XSENSOR® Technology Corporation. The pad was constructed of a flexible plastic which is pliable and detachable from the electronics. The X2 model was tested using a smart media card and a serial port. The pad model was an X36 pad referring to a 36 by 36 sensor arrangement, measuring 45.72 cm by 45.72 cm with a pad thickness of less than 1 mm. The sensor pad was composed of 1296 individual capacitive sensors capable of a pad scan rate across all sensors of 27 times per second using the smart media card to increase the sampling rate. The recommended pressure range was between 1.33-26.66 kPa (10-200 mmHg). The system was newly calibrated by the manufacturer since a calibration device is not currently available for purchase. The system also came with software calibration files created by the manufacturer.

The piezoresistive technology tested is the medical seat UT model, manufactured by Vista Medical Limited. The pressure pad was made of a thin (0.36 mm thick) elastic-covered fabric measuring 53.34 cm by 53.34 cm comprising a 16 by 16 cm sensor array. Each pad has 256 piezoresistive sensors which are all scanned at a rate of 12 times per second. The system is sold with a laptop computer and associated software (currently version 3.1). The manufacturer recommends testing for this seat pad for pressures in the range of 0 - 26.66 kPa (0 – 200 mmHg). The system was newly calibrated by the manufacturer, although a calibration kit is available for purchase with the system.

For each sensor pad, three test protocols were performed in a randomized order, as follows: an incremental loading test, a low threshold test, and a creep test. The software for all pressure systems was programmed to collect data at 1 sample/s. A 3 mm Bocklite cushion was placed over a wooden table and the pressure pad was placed on top of the Bocklite. All sensor pads were marked prior to testing by the researcher to ensure that the loads were placed on the same location on the pressure pad for each test. This ensures that the same sensors are activated and consistency is maintained within each test and between tests. Figure 1 illustrates the experimental set up of a load applied to a marked pressure pad.

Figure 1: Experimental set up of a 9.392 kg load on the XSENSOR® pressure pad.

For statistical analysis, all protocols were analyzed using SPSS 9.0 software. Means and standard deviation were calculated for each load. All data were normalized by dividing the measured means of the pressure system by theoretical predicted value of the load, to allow for comparison of the accuracy between different systems. The level for statistical significance was $p \leq 0.05$.

4.1 Incremental Loading Test

For the incremental protocol, the pressure pads were loaded and unloaded in the following sequence: unloaded for 1 minute, loaded with 9.392 Kg for 2 minutes (step 1), unloaded for 1 minute, loaded with 9.392 kg for 2 minutes (step 2), unloaded for 1 minute, loaded with 9.392 kg for 2 minutes (step 3), unloaded for 2 minutes, loaded with 9.392 Kg for 2 minutes (step 4), loaded with 13.992 Kg for 2 minutes (step 5), loaded with 18.627 Kg for 2 minutes (step 6), loaded with 13.992 Kg for 2 minutes (step 7), loaded with 9.392 Kg for 2 minutes (step 8), unloaded for 2 minutes, loaded with 9.392 Kg for 2 minutes (step 9), unloaded for 2 minutes, loaded with 13.992 Kg for 2 minutes (step 10), unloaded for 2 minutes, loaded with 18.627 Kg for 2 minutes (step 11), unloaded for 2 minutes, loaded with 19.627 Kg for 2 minutes (step 12), unloaded for 2 minutes, loaded with 14.992 Kg for 2 minutes (step 13), unloaded for 2 minutes, loaded with 10.392 Kg (step 14) and unloaded for 1 minute. In all, 14 loaded conditions or steps were produced, whereby each time the sensor pad was loaded, the software indicated a step for the given load. For each step produced, the middle 50% of the samples collected, gathered at 1 sample/s, were used for statistical analysis. This was done to eliminate transient data resulting from transitions or settling between the unloaded and loaded conditions. Analyzed data from each sensor were used to calculate means, standard deviations and normalized values. A 1-way ANOVA was performed to compare differences between steps. A Tukey HSD Post Hoc test was used to identify differences between given steps. A Levene Statistic was used to test for homogeneity of variances for the all of the steps to ensure appropriate comparison between steps.

4.2 Low Threshold Test

For the low threshold protocol, each pressure system was tested at a pressure that was 1 unit of pressure above the manufacturer's recommended lowest threshold, to objectively evaluate whether or not the manufacturer's threshold standards were correct. For the FSA system, the minimum recommended low threshold for testing was a pressure greater than 1.2% of the maximum calibrated pressure file. Since the maximum calibration file used during testing was 13.33 kPa (100mmHg written by the manufacturer), the FSA system was tested at 0.29 kPa (2.2 mmHg). For the F-Scan system, the manufacturers recommended range was from 0-241.32 kPa (0-35 PSI written by the manufacturer); therefore the system was tested at 6.89 kPa (1 PSI). For the XSENSOR® system, the minimum recommended low threshold for testing was 1.33 kPa (10 mmHg written by the manufacturer); therefore, the system was tested at 1.47 kPa (11 mmHg). All data were normalized by dividing the measured means of the pressure

system by theoretical predicted value of the load, to allow for comparison of the accuracy between different systems.

Data were recorded from each system using the predetermined light load, in the following sequence: one minute unloaded, 20.0 minutes loaded, and one minute unloaded. The software graphed one 20 minute step for this test. For the step produced, the middle 50% of the samples collected were used for statistical analysis. The analyzed data were used to calculate means, standard deviations and normalized values. A regression equation was graphed and the R^2 value was calculated using MS Excel®. For the regression equation, the independent variable (x value) was time (in seconds) and the dependant variable (y value) was pressure (in kPa) as measured by the pressure pad.

4.3 Creep Test

The creep test protocol involved placing an 18.627 Kg load on the predetermined marked area of the sensor pad. For one minute at the start of the test (before the sensor was loaded) and for one minute at the end of the test (after the load was removed) the sensor was unloaded and data were recorded to ensure the sensor was responding properly in the no load condition. The software graphed one step for a 58.8 minute creep test. For the step produced, statistical analysis was perform on the middle 50% of the samples collected, the last 25% of the samples collected, and 100% of the samples collected (at 1 sample/s). This was done to examine which data set gave the most accurate results over the extended duration. The data were used to calculate means, standard deviations and normalized values, and percentage of creep. A regression equation was graphed and the R^2 value was calculated using a MS Excel®. For the regression equation, the independent variable (x value) was time (in seconds) and the dependant variable (y value) was pressure (in kPa) as measured by the pressure pad.

5.0 Results

5.1 Incremental Loading Test

A 1-way ANOVA analysis performed on the FSA data showed statistical differences between steps ($p<0.01$; $F=65880.6$). A Tukey HSD Post Hoc showed that these differences were a result of significant differences between all steps except steps 1 and 2 ($p=1.0$) and steps 2 and 3 ($p=1.0$). F-Scan data also showed statistical differences between steps ($p<0.01$; $F=4090.2$). A Tukey HSD Post Hoc showed that these differences were a result of differences between all steps except steps 2 and 3 ($p=0.058$), steps 4 and 5 ($p=0.925$), steps 8 and 9 ($p=0.997$), steps 10 and 11 ($p=1.0$), steps 10 and 13 ($p=1.0$), and steps 11 and 13 ($p=0.998$). Analysis of the XSENSOR®, also showed statistical differences between steps ($p<0.01$; $F=79454.7$). A Tukey HSD Post Hoc showed significant differences between all steps. A Test for Homegeniety of Variance, for all

steps analyzed by for each system, showed that all steps were significantly homogeneous ($p \leq 0.01$).

A typical output pattern of data as collected by XSENSOR® is shown in Figure 2. Table 1 numerically represents steps graphed in Figure 2 and compares measured and predicted data for each system during testing. Table 2 summarizes normalized data for each system.

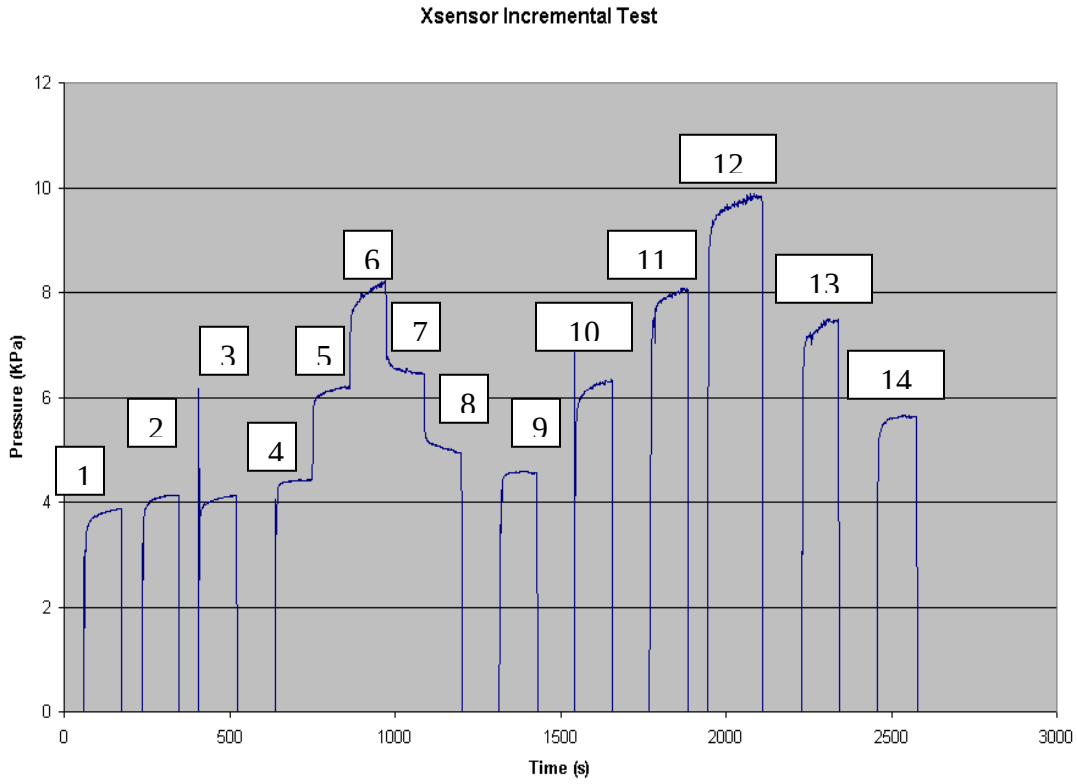

Figure 2: A typical output pattern of data collected during incremental testing produced by XSENSOR®. The step number assigned is displayed above each step.

Table 1 - Measured and predicted data for each system during incremental testing.

Step Number	Predicted (kPa)	Measured FSA (kPa)	Measured F-Scan (kPa)	Measured XSensor (kPa)
1	5.93	4.32 ± 0.04	15.42 ± 0.59	3.78 ± 0.04
2	5.93	4.32 ± 0.04	14.28 ± 0.49	4.09 ± 0.03
3	5.93	4.32 ± 0.05	14.03 ± 0.19	4.06 ± 0.03
4	5.93	4.43 ± 0.04	19.82 ± 0.40	4.40 ± 0.01
5	8.84	6.50 ± 0.06	19.94 ± 0.23	6.13 ± 0.03
6	11.77	8.10 ± 0.05	23.16 ± 0.31	8.00 ± 0.08
7	8.84	6.84 ± 0.04	20.95 ± 0.23	6.50 ± 0.03
8	5.93	4.90 ± 0.04	19.10 ± 0.03	5.04 ± 0.04
9	5.93	4.36 ± 0.05	19.02 ± 0.52	4.57 ± 0.009
10	8.84	6.68 ± 0.04	22.52 ± 0.56	6.20 ± 0.06
11	11.77	8.46 ± 0.07	22.48 ± 0.50	7.92 ± 0.06
12	12.40	8.87 ± 0.06	25.62 ±0.40	9.67 ± 0.05
13	9.47	7.27 ± 0.05	22.56 ± 0.60	7.34 ± 0.10
14	6.56	5.08 ± 0.06	18.12 ± 0.29	5.62 ± 0.02

Table 2 – Normalized data for each system.

Steps Measured	FSA Normalized	F-Scan Normalized	XSensor Normalized
1-3	0.729	2.46	0.671
4, 8, 9	0.770	3.26	0.788
5, 7, 10	0.755	2.39	0.710
6, 11	0.704	1.94	0.676
14	0.715	2.76	0.780
13	0.767	2.38	0.775
12	0.774	2.07	0.857
Composite Average (1-14)	0.745	2.47	0.751
Composite Standard Deviation	0.0285	0.440	0.0680

5.2 Low Threshold Test

Figure 3 summarizes regression equations and R^2 values when middle 50% of data samples were analyzed from each system. The mean and standard deviation values for each system are given in Table 3.

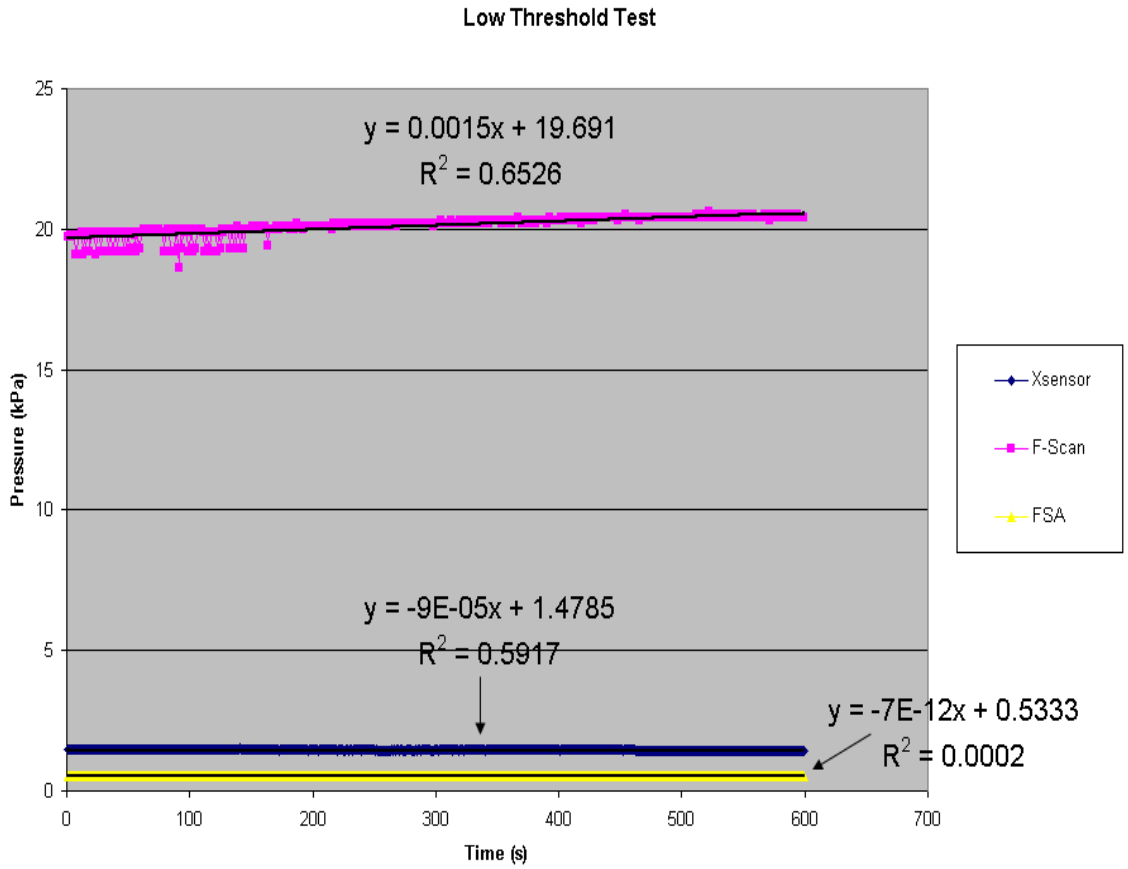

Figure 3: Regression equations and R2 values for each system during low threshold testing.

Table 3 – Measured, predicted and normalized data for each system during low threshold testing.

Test Outcomes	FSA	F-Scan	XSENSOR®
Expected (kPa)	0.295	6.89	1.47
Measured test (kPa)	$0.533 \pm 7.62 \times 10^{-8}$	20. 14 ± 0.320	1.51 ± 0.02
Normalized Initial Test	1.81	2.92	1.03

5.3 Creep Test

Table 4 summarizes the results measured when 100%, the middle 50% and the last 25% of the sampled data were analyzed. This table shows that normalized samples using the last 25% of samples collected, approaches the predicted (expected) outcome more closely than other analysis methods listed. Figure 4 summarizes the regression equation and R^2 values for all the pressure systems. Overall creep characteristics for each system were found to be 19.54% for the FSA, 17.23 % for the F-Scan, and 17.62 % for the XSENSOR®.

Table 4: Expected, measured and normalized data of all systems during creep testing.

Test Outcomes	FSA	F-Scan	XSENSOR®
Expected (kPa)	11.77	11.77	11.77
Measured mid 50% of data (kPa)	8.92 ± 0.054	26.89 ± 0.40	8.90 ± 0.12
Measured last 25% of data (kPa)	9.04 ± 0.019	26.89 ± 0.31	9.15 ± 0.051
Measured 100% of data (kPa)	8.80 ± 0.43	26.74 ± 0.76	8.84 ± 0.31
Normalized (mid 50%)	0.758	2.29	0.756
Normalized (last 25%)	0.768	2.29	0.778
Normalized (100%)	0.748	2.27	0.751

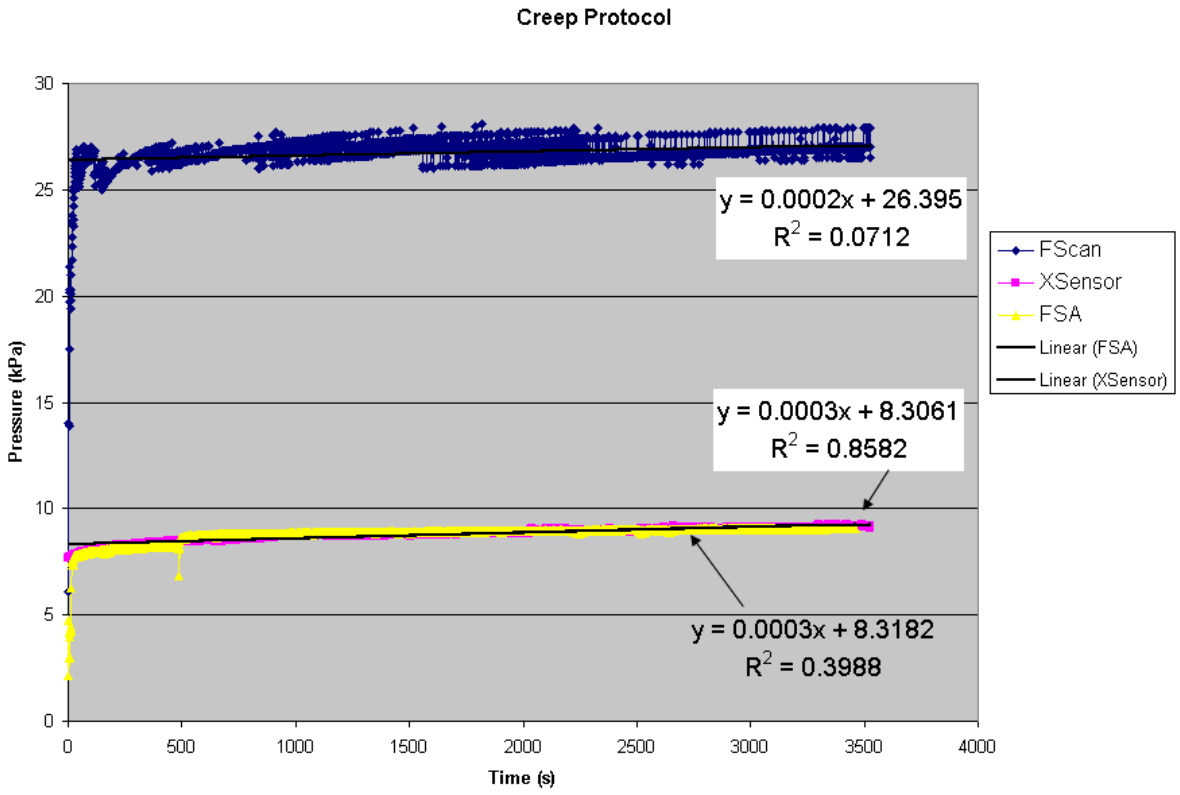

Figure 4: Regression equations and R2 values for each system during creep testing.

5.4 Comparison of Systems for all Test Conditions

The normalized data from each test (incremental, low threshold and creep) was combined to give an overall performance score for each system. The "Overall Score" summarised in Table 5, reflects the average normalized value from all test conditions.

Table 5: Comparison of normalized data for systems during incremental, low threshold, and term creep testing.

Normalized Data	FSA	F-Scan	XSENSOR®
[a]Incremental Test	0.745	2.47	0.751
Low Threshold Test	1.81	2.92	1.03
[b]Creep Test	0.768	2.29	0.778
Overall Score (Average of All Tests)	1.11	2.56	0.853

[a] This value is the average normalized value for all steps 1 though 14
[b] This data were calculated using the last 25% of data

6.0 Discussion

6.1 Incremental Test

Error in a measured quantity, verses the desired or actual value, can be expresses in terms of bias and variance. Bias is a measure of the offset of the reported value with respect to the true value. Variance is a measure of how much the data points vary about the mean value – this is reported as variance, standard deviation and/or coefficient of variation (standard deviation / mean). There is a substantial bias error in the data reported by all three pressure measurement systems in the incremental testing. In all cases, the FSA and XSENSOR® systems underestimated the applied pressure and the F-scan system overestimated the applied pressure. The bias and percent bias error are given in Table 6. The bias error is calculated as the difference between the mean measured pressure and the applied pressure. The percent bias is calculated using the following equation:

$$\%\text{bias} = \frac{\text{Measured Pressure} - \text{Applied pressure}}{\text{Applied Pressure}} \times 100$$

Table 6: Bias and %bias error in the mean pressure values reported by the three pressure measurement systems.

Step Number	**Applied Pressure**	**FSA**		**F-scan**		**XSENSOR®**	
		Bias	% Bias	Bias	% Bias	Bias	% Bias
1	5.93	-1.61	-27.2	9.49	160.0	-2.15	-36.3
2	5.93	-1.61	-27.2	8.35	140.8	-1.84	-31.0
3	5.93	-1.61	-27.2	8.10	136.6	-1.87	-31.5
4	5.93	-1.50	-25.3	13.89	234.2	-1.53	-25.8
5	8.84	-2.34	-26.5	11.10	125.6	-2.71	-30.7
6	11.77	-3.67	-31.2	11.39	96.8	-3.77	-32.0
7	8.84	-2.00	-22.6	12.11	137.0	-2.34	-26.5
8	5.93	-1.03	-17.4	13.17	222.1	-0.89	-15.0
9	5.93	-1.57	-26.5	13.09	220.7	-1.36	-22.9
10	8.84	-2.16	-24.4	13.68	154.8	-2.64	-29.9
11	11.77	-3.31	-28.1	10.71	91.0	-3.85	-32.7
12	12.40	-3.53	-28.5	13.22	106.6	2.73	-22.0
13	9.47	-2.20	-23.2	13.09	138.2	-2.13	-22.5
14	6.56	-1.48	-22.6	11.56	176.2	-0.94	-14.3

A plot of bias error verses applied pressure for the three systems is shown in Figure 5 along with the regression equations and R^2 values for each system. It is evident that the bias error in the FSA and XSENSOR® systems are correlated with applied pressure while the bias error in the F-scan system is not correlated with applied pressure. Since the bias error at zero applied pressure for all three systems should be zero, the non-zero intercept

indicated that the sensor response changes as zero pressure is approached. This is evident in the low threshold tests. The R^2 values for the %bias verses applied pressure for the XSENSOR® and FSA systems are 0.027 and 0.194 respectively. These low values indicate that the %bias is not correlated with applied pressure for these systems. Because of the large bias error, the %bias for the F-scan system varies widely from a low of 91% to a high of 234%.

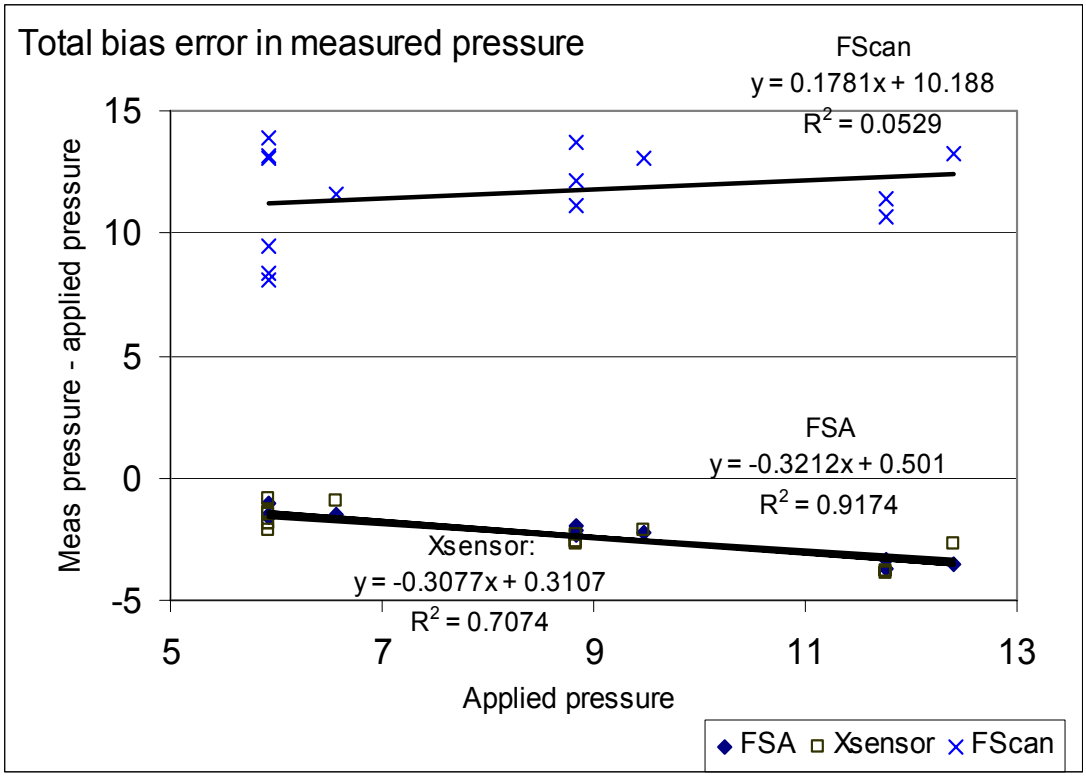

Figure 5: Total bias error verses applied pressure for the incremental testing.

The performance of the F-scan in this study is worse than previously reported, where F-scan inaccuracies ranged from 30 to 62% (Hadcock, 2002; Luo et al., 1998; Morin et al., 2001; Polliack et al., 2000; Sih, 2001; Sumiya et al., 1998). Others have reported that the FSA is more accurate than the F-scan (Ferguson-Pell and Cardi, 1991), the XSENSOR® is more accurate than the F-scan (Hochmann et al., 2002), and the XSENSOR® and FSA systems performed with similar accuracy under a variety of load conditions (Hochmann et al., 2002). Our findings are consistent with these reports.

It should be noted, however, that the XSENSOR® in this study appeared to be noticeably less accurate than the FSA at the very beginning of the incremental testing (ie. steps 1-3 at 5.93 kPa). This data suggest that a warm up period for the XSENSOR® pressure sensing system may be necessary. The initial inaccuracy for the XSENSOR® may have been due to the nature of the technology used for the system. Since XSENSOR®

technology uses two pressure sensing elements or plates, a warm up period may be needed to equilibrate the charge between the sensing plates. When the system is fully charged, an applied load acting on the sensing elements decreases the separation between the plates, thereby changing the capacitance (ability to store charge), which is continually measured by the electronic equipment. Therefore, at the start of testing, there may be some fluctuation of the electric charge as the sensors settle, a factor that may have affected performance for the short duration testing (ie. 2 minute loading periods). In contrast, the FSA is made of a piezoelectric material and responds to an applied pressure by generating a voltage output; therefore, equilibration of charge is not required. This may explain the greater accuracy of the FSA system at the initial stages of testing; although, this idea is based on limited information regarding the underlying pressure sensing technology.

The XSENSOR® and FSA showed no basic pattern of repeatability for a given pressure in this study. This finding does not have a logical explanation, since the accuracy was acceptable, the loading method was highly controlled, and the masses used for testing were identical. Further it is also difficult to assess why repeatability would have been poor since there are currently no objective and controlled studies on repeatability of the systems tested in this report. Perhaps the incremental tests were too short in duration (2 minute loading) for the electrically charged capacitance-sensing elements of the XSENSOR®, to settle in a consistent manner, when the fixed load was applied and then reapplied. However, this does not explain the poor repeatability of the piezoresistive system too, since the electric signal is immediately generated and collected when the piezo-material is loaded. The piezoresistive FSA system did show statistical similarities between the initial 3 loads at 5.93 kPa and this finding may be due to the properties of the peizoresistive material of the FSA. The repeatability of the F-scan system was also found to be poor in this study, although this finding was not surprising and was consistent with others (Lu and Lin, 1996; Smith et al., 2002; Woodburn & Helliwell, 1996). It should be noted that the short settle times (i.e. 2 minutes in duration) are not recommended by the manufacturer. For many load carriage situations, it would not be difficult to delay sampling at the initial aspect of a study.

In short, the FSA and XSENSOR® pressure sensing systems measure short duration pressures between in the range of 5.93 kPa through 12.40 kPa with reasonable accuracy; however, both systems underestimate actual predicted pressures and this measurement error must be accounted for through corrections in the mechanical hardware or through software corrections. For each system tested, repeatability is a concern and improvements should be made to the systems in this area as well.

6.2 Low Threshold Test

For low threshold testing, the XSENSOR® was highly accurate compared to the FSA and F-Scan technology. The advantage of the XSENSOR® for light threshold testing may be due to the properties of capacitance sensors. Since capacitance sensors measures stored charge (capacitance) between small sensing plates, only light pressures are required to cause small changes in the distance between the plates and the system easily detects these

light pressures through small changes in capacitance. In contrast, a piezoresistive sensor requires a charge amplifier to measure the charge emitted during loading, so light loads may not be suitably measured and amplified (Cavanagh et al., 1992). In contrast, the F-Scan ink technology was inadequate to measure light loads, making it inappropriate for dealing with light pressures. In fact, at light loads the F-scan system overestimated loads by 3 times the actual predicted load. It may be possible, however, to correct these problems if each manufacturer methodologically tests the actual, not theoretical, low threshold of each system, and makes the appropriate changes to the recommendations in the owner's manual.

When all sensing systems are compared based on the linear equation and R^2 value, the XSENSOR® is superior overall at the low threshold pressures. Specifically, the R^2 for the XSENSOR® and FSA were small ($R^2<0.59$) demonstrating that the proportion of variance in pressure was not explained by time. This finding is highly desirable for a testing system, since a superior system should be related only to the amount of pressure placed on the sensor, rather than to the amount of time that a load was allowed to settle on the sensor. In contrast, the F-Scan (Figure 3) showed a sizable proportion of variance in pressure that was explained by time ($R^2=0.6526$). Further, the linear equation in Figure 3 shows an extremely small slope for the XSENSOR® and FSA system (less than -9×10^{-5}), which means that both systems show very small drift at low pressure compared to the F-scan. Last, the XSENSOR® and FSA systems show very small bias in the linear equation (small y-intercept) compared to the F-scan, which resulted in improved accuracy for both the XSENSOR® and FSA systems for measuring low threshold. In short, the XSENSOR® was most stable, most accurate, and had less bias and variability at low pressures. In contrast, the F-Scan system was the most unstable, most inaccurate, and had the highest bias and variability.

6.3 Creep Test

A large number of samples were collected during creep testing and data were analyzed differently to determine which method of analysis would lead to most accurate results. Results showed that measuring and analysing the last 25% of the samples collected for the XSENSOR® and FSA system, lead to more accurate measurements, as reflected in the normalized value approaching 1.0. However, both these systems underestimated the actual predicted load and demonstrated a significant positive creep (19.54% for the FSA and 17.62% for the XSENSOR®), as the load was allowed to settle over time. This means that over time, the output of the FSA and XSENSOR® systems rises towards the actual applied pressure and that the researcher should consider allowing the sensor to settle before recording the output data. These results indicate that the pressures reported for short duration tests, dynamic tests or incremental tests may be inaccurate since the sensors do not respond instantaneously to changes in pressure, but rather settle to a steady state value over time. Further, the F-Scan showed both significant creep stability over time at 17.23%, and a substantial overestimation of the actual predicted load over time. The F-Scan results found in this study were similar to those reported in the literature where creep ranging from 12% to 20% has been documented (Ferguson-Pell and Cardi, 1991; Ferguson-Pell and Cardi, 1993; Polliack et al., 2000).

Analysis of the R^2 values for each system, also shows that time does not explain much of the variation in pressure for the FSA and F-Scan systems (R^2 = 0.45 for FSA, R^2=0.071 for F-Scan); showing that creep is less of a problem over time for these systems. In contrast, a sizable amount of the variation in pressure was explained by time for the XSENSOR® (R^2=0.86), suggesting that even after 58.8 minutes, the XSENSOR® sensing elements are continually settling towards a steady-state value. Despite the higher creep characteristics for all systems, particularly the XSENSOR®, it may be possible to create mathematical algorithms in the software to correct these problems**.**

6.4 Comparison of all Systems

The normalized data from each test (incremental, low threshold and creep) were combined to give an overall performance score for each system based on quantitative, objective data collected during this study. Considering the normalized data listed in Table 2, the FSA and XSENSOR® performed similarly, given that both systems had a normalized value near 1.0. However, the XSENSOR® appears to be the most suitable and accurate system for research purposes that require measurement of a variety of pressures (low through high). The FSA may also be a suitable instrument for research purposes, although it is not recommended for light pressure testing near the manufacturer stated low threshold value. In contrast, the F-Scan results demonstrate that the F-Scan is too inaccurate and not suitable for research purposes where absolute pressures are needed under all the testing conditions used. It should be noted, however, that there are some technical limitations involving creep and repeatability characteristics of the FSA and XSENSOR® systems which need to be addressed. Nonetheless, it may be possible to either modify the hardware, or more likely, to modify the software by creating mathematical algorithms to decrease the amount of creep over time and to improve repeatability characteristics for these systems.

The overall operation of the software packages provided with the XSENSOR®, the FSA and the F-scan systems were also evaluated during testing. The XSENSOR® and FSA software packages provided simple, clear instructions as well as easy recording, viewing and exporting of the data. Technical support at the companies gave fast and efficient help. The F-scan software was more challenging to operate, since the steps in the software required for setting the calibration files and manipulating the data are not clear. In both the FSA and XSENSOR® systems the image resolution can be increased by custom building a sensor pad with more sensors; however the F-scan does not have this capability.

There are some significant drawbacks for the FSA system as a research instrument, when compared to the XSENSOR®. First, the FSA system cannot be programmed to measure in SI units (measurements are in mmHg only), whereas the XSENSOR® can report data collect in both SI units and imperial units. The second drawback and most significant problem with the FSA system is the method by which the software collects and reports the time of each sample collected. When data are imported into a spreadsheet, the user

must edit each time sample to remove the day, the hour and the minutes linked to each sample. The timing data are represented in the spreadsheet in such a way that a macro file cannot be used to automate the conversion, necessitating further manipulation. As well, the software does not collect data starting at time zero. The XSENSOR® system has the same problem with date and time information, although improvements are currently being made to have the system start sampling the data at zero time.

7.0 Conclusions

In summary, the XSENSOR® and FSA pressure measurement systems were superior to the F-Scan system in terms of accuracy and creep characteristics for pressures applied with the sensor on a flat surface. Also, the XSENSOR® performed better than other two systems at low threshold pressures and the XSENSOR® software provides ease of use and flexibility in data reporting. The main drawback for all of the pressure systems at this time is the long settling time needed to get more accurate data due to creep. For use in human load carriage, there will need to be adjustments in amplitude, and creep characteristics. There will also need to be research to determine whether these systems can be use to measure pressure on a curved surface, such as the shoulder and waist belt (Fergenbaum et al., 2003). It will also be necessary to know its responses under dynamic conditions (Fergenbaum et al., 2003).

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(U) A variety of pressures mapping technologies have been used to assess contact pressures between human tissues and solid flat surface materials. However, research on the accuracy, repeatability, and creep for these technologies is limited. Three commonly used technologies were evaluated for accuracy, repeatability, and creep on a flat surface under highly controlled laboratory conditions. The systems tested included a resistive ink technology known as the F−scan F−socket (Tekscan Incorporated), a piezoresistive technology known as the FSA seat mat (Vista Medical, Limited), and a capacitance technology known as the XSENSOR® seat mat (XSENSOR® Technology Corporation). Loads between 9.392 kg and 19.627 kg were placed on each sensor using three standardized protocols: an incremental, a low threshold and a creep protocol. For overall accuracy during incremental loading, FSA mat measured a pressure that was 74.5% of the actual applied pressure, the F−scan measured a pressure that was 247.0% of the actual applied pressure and the XSENSOR® measured a pressure that was 75.1% of the actual applied pressure. The overall accuracy for low threshold testing, found that the FSA mat measured a pressure which was 181.0% of the actual applied light pressure, the F−scan measured a pressure which was 292.0% of the actual applied light pressure and the XSENSOR® measured a pressure that was 103% of the actual applied light pressure. Creep characteristics as a percentage were found to be 19.54% for the FSA mat, 17.23 % for the F−Scan, and 17.62 % for the XSENSOR®. No pattern of repeatability was found. In summary, the XSENSOR® and FSA pressure measurement systems were superior to the F−Scan system in terms of accuracy, although the XSENSOR® was more accurate than the other two systems at low threshold pressures. The main drawback of each system at this time is the long settling time needed to get more accurate data due to creep. This needs to be corrected within the software of each system. For use in human load carriage, there will need to be adjustments in amplitude and creep characteristics.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) Load carriage; Dynamic Biomechanical Model; Pressure measurement System; XSENSOR®; F−Scan