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Interface shear and pressure characteristics of wheelchair seat cushions

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Abstract—Pressure ulcer incidence rates have remained constant despite advances in support surface technology. Interface shear stress is recognized as a risk factor for pressure ulcer development and is the focus of many shear reduction technologies incorporated into wheelchair cushions; however, shear reduction has not been quantified in the literature. We evaluated 21 commercial wheelchair seat cushions using a new methodology developed to quantify interface shear stress, interface pressure, and horizontal stiffness. Interface shear stress increased significantly with applied horizontal indenter displacement, while no significant difference was found for interface pressure. Material of construction resulted in significant differences in interface shear stress, interface pressure, and horizontal stiffness. This study shows that the existing International Organization for Standardization (ISO) 16840-2 horizontal stiffness measure provides similar information to the new horizontal stiffness measure. The lack of a relationship between interface shear stress and the overall horizontal stiffness measure, however, suggests that a pressure and shear force sensor should be used with the ISO 16840-2 horizontal stiffness measure to fully quantify a cushion's ability to reduce interface shear stress at the patient's bony prominences.

Key words: decubitus ulcer, interface, pressure, pressure sore, pressure ulcer, shear force, shear stress, stiffness, support surface, wheelchair seat cushion.

INTRODUCTION

In the United States, annual pressure ulcer treatment costs have risen from $1.34 billion in 1992 [1] to approximately $17.2 billion in 2003 [2], with nearly 90 percent billed to Medicare or Medicaid. In 2003, approximately 455,000 hospital stays were caused principally by pressure ulcers and 167,000 hospital stays were for paralysis and/or spinal cord injury (SCI) [2]. The average hospital charge per stay was $37,800, resulting in $6.3 billion in treatment costs for the SCI population. With constant incidence rates of approximately 7.6 percent from 1999 to 2004 [3], pressure ulcer prevention is essential.

Wheelchair seat cushions are designed to provide comfort and aid against pressure ulcer development [4]. To aid against pressure ulcers, cushions are designed to reduce extrinsic risk factors known to increase the risk of pressure ulcers. The mechanical extrinsic risk factors are pressure and shear [5]. Literature is available on the interface pressure and pressure redistribution characteristics of commercial cushions [6–7]; however, no study has evaluated interface shear stress of commercial cushions. Animal and human studies have demonstrated that shear forces

Abbreviations: HCPCS = Healthcare Common Procedure Coding System, ICC = intraclass correlation coefficient, ISO = International Organization for Standardization, IT = ischial tuberosity, NIDRR = National Institute on Disability and Rehabilitation Research, RCLI = rigid cushion loading indenter, SCI = spinal cord injury, TTC = The Technology Collaborative, VE = viscoelastic.

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compromise tissue integrity. The animal studies identified that shear forces applied to bony prominences increased the severity of pressure ulcers compared with pressure alone [8–9], and the human studies identified that shear forces decreased cutaneous blood flow [10–13]. The literature has established the importance of reducing shear; yet no previous study has evaluated interface shear stress of commercial cushions. Information on this cushion characteristic may aid clinicians in selecting the appropriate cushion to meet their patients' needs and benefit cushion designers with a technique to quantify shear reduction. The International Organization for Standardization (ISO) published a standardized method for measuring the horizontal stiffness of seat cushions. The rationale for the ISO standard is that the degree of horizontal stiffness a cushion has relates to the amount of shear stress imparted by the cushion to the patient's soft tissue [14]. The purpose of this study was to quantify interface shear stress, interface pressure, and horizontal stiffness for commercial wheelchair seat cushions and determine whether a relationship exists between interface shear stress and horizontal stiffness of cushions.

METHODS

Cushions

Twenty-one cushions representing all Healthcare Common Procedure Coding System (HCPCS) categories, except custom-fabricated seat cushions (E2609), were evaluated in this study (**Table 1**). Categories included general use (E2601), adjustable/nonadjustable skin protection (K0734/E2603), positioning (E2605), and adjustable/nonadjustable combination skin protection and positioning cushions

Table 1.
Wheelchair seat cushions listed by Healthcare Common Procedure Coding System (HCPCS) category.

HCPCS Code	Product Name	Cushion Cover	Manufacturer	Model Number	Material(s) of Construction
E2601	MOSAIC	Standard two-way stretch	ROHO*	MOS1616C	Segmented air cell
	Jay Basic	Incontinence resistant	Sunrise Medical†	305-MJ	Contoured elastic foam
	Curve	Comfort-Tek	Comfort Company‡	463G-1616-B	Contoured elastic foam
	Stimulite Silver	Polyester	Supracor§	SI1616	Honeycomb
K0734	HIGH PROFILE Single Compartment	Standard two-way stretch	ROHO	IR99C	Segmented air cell
	Adjuster	Comfort-Tek	Comfort Company	AJ-F-1616	Independent air cell
	Jay J2 Deep Contour	Ballistic stretch	Sunrise Medical	2466	Viscous fluid/contoured elastic foam
E2603	TRIUMPH	Standard two-way stretch	ROHO	TS1616C	Viscoelastic foam
	Ascent	Comfort-Tek	Comfort Company	HY-GF-1616	Contoured elastic foam
	Jay Xtreme	LoShear	Sunrise Medical	966LS	Viscous fluid/contoured elastic foam
	Stimulite Classic	Polyester	Supracor	CL1616/SP1616	Honeycomb
E2605	AirLITE	Standard two-way stretch	ROHO	AL1616	Elastic foam and segmented air cell
	Ridge	Comfort-Tek	Comfort Company	RD-F-1616	Viscoelastic and elastic foam
	Jay Soft Combi P	Incontinence resistant	Sunrise Medical	B2205 (15.5 × 16)	Contoured elastic foam
K0736	HIGH PROFILE QUADTRO SELECT	Standard two-way stretch	ROHO	QS99C	Segmented air cell
	Vector	Comfort-Tek	Comfort Company	VT-F-1616	Independent air cell
	Jay J2 Deep Contour P	Ballistic stretch	Sunrise Medical	2466P	Viscous fluid/contoured elastic foam
E2607	Harmony	Standard two-way stretch	ROHO	H1616C	Segmented air cell
	Maxx	Comfort-Tek	Comfort Company	MAXFF-1616	Gel and elastic foam
	Jay Easy	Incontinence resistant	Sunrise Medical	JE1616C	Viscous fluid/contoured elastic foam
	Stimulite Contoured	Polyester	Supracor	CD1616	Honeycomb

*The ROHO Group, Inc; Belleville, Illinois.
†Sunrise Medical, Inc; Longmont, Colorado.
‡The Comfort Company; Bozeman, Montana.
§Supracor, Inc; San Jose, California.

(K0736/E2607) [15]. Cushions were chosen from manufacturers with a large market share. The ROHO Group, Inc, (Belleville, Illinois); Sunrise Medical, Inc, (Longmont, Colorado); and The Comfort Company (Bozeman, Montana) each have at least one cushion in each HCPCS category, and Supracor, Inc, (San Jose, California) has at least one cushion in each nonadjustable category. Supracor was chosen specifically because it does not offer adjustable cushions. A shear-reducing cushion cover was chosen for each cushion when available.

Instrumentation

Shear and pressure characteristics of the cushions were obtained using a test apparatus (**Figure 1**) that consisted of a (1) Material Test System (MTS Systems Corp; Eden Prairie, Minnesota); (2) load cell (MTS Systems Corp); (3) loading rig; (4) rigid cushion loading indenter (RCLI); (5) digital indicator (Swiss Precision Instruments, Inc; Garden Grove, California); and (6) pressure and shear force sensor (Predia, Molten Corp; Hiroshima, Japan). The loading rig was capable of applying a vertical load of up to 830 N (±10 N) to the cushions via the RCLI, measuring vertical and horizontal displacements (±1 mm) of the RCLI, and supporting a wheelchair seat cushion on a rigid horizontal surface without flexing. The RCLI was manufactured from fiberglass with dimensions as specified in "Annex A" of ISO 16840-2 [14]. Interface pressure and interface shear force were measured from the pressure and shear force sensor (10 Hz), and horizontal force was measured with the load cell (10 Hz). The pressure and shear force sensor (sensor) was adhered just anterior to the left ischial tuberosity (IT) of the RCLI with double-sided tape. The location provided a flat, rigid surface to avoid bending of the sensor.

The sensor measured pressure with air displacement and shear force with a strain gauge. The sensor is made of flexible plastic and is elliptical in shape (**Figure 2**). The sensor has an analog output for data collection and internal memory for storing up to five pressure and shear measurements. The sensor measured pressure ranging from 0 to 200 mmHg and shear force ranging from 0 to 50 N. Interface shear stress was calculated by dividing interface shear force by the shear-sensing area (28.14 cm^2).

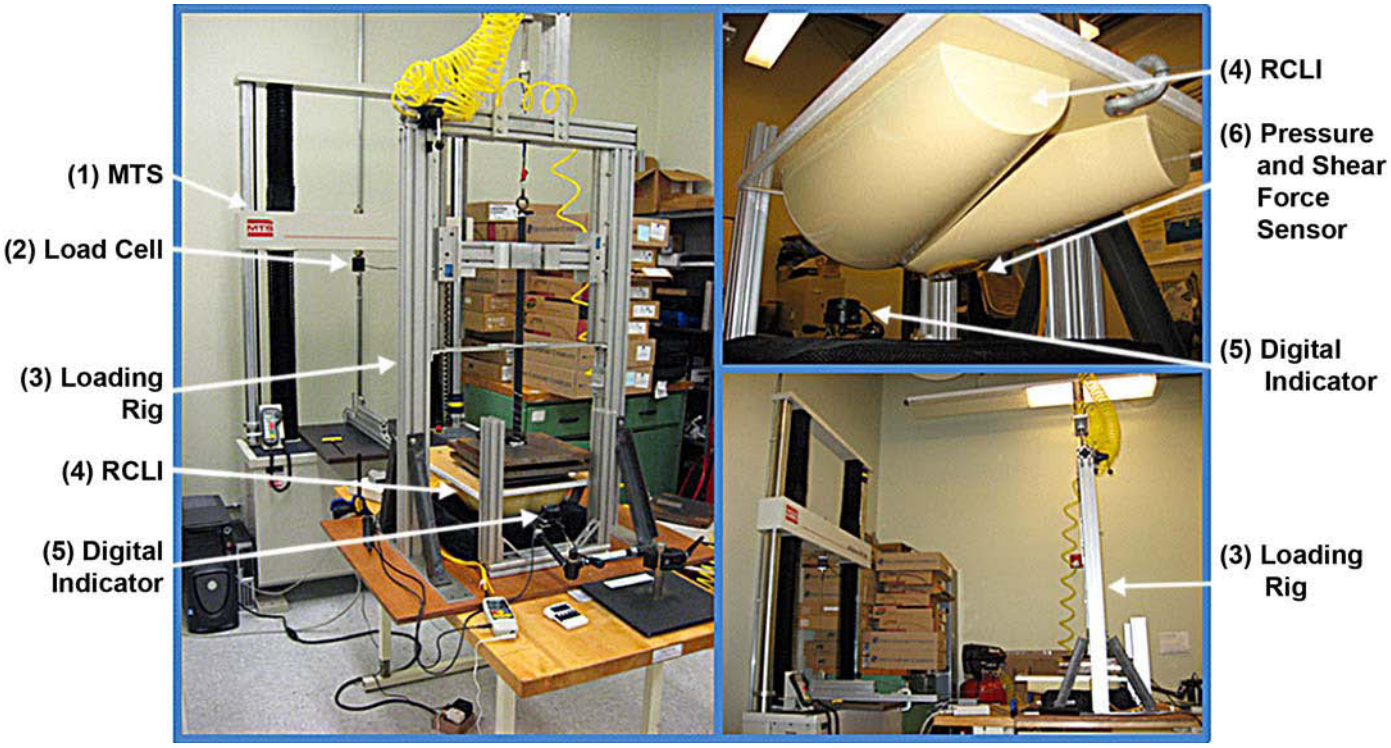

Figure 1.
Test apparatus to obtain shear and pressure characteristics of wheelchair seat cushions. Apparatus consisted of (1) Material Test System (MTS), (2) load cell, (3) loading rig, (4) rigid cushion loading indenter (RCLI), (5) digital indicator, and (6) pressure and shear force sensor.

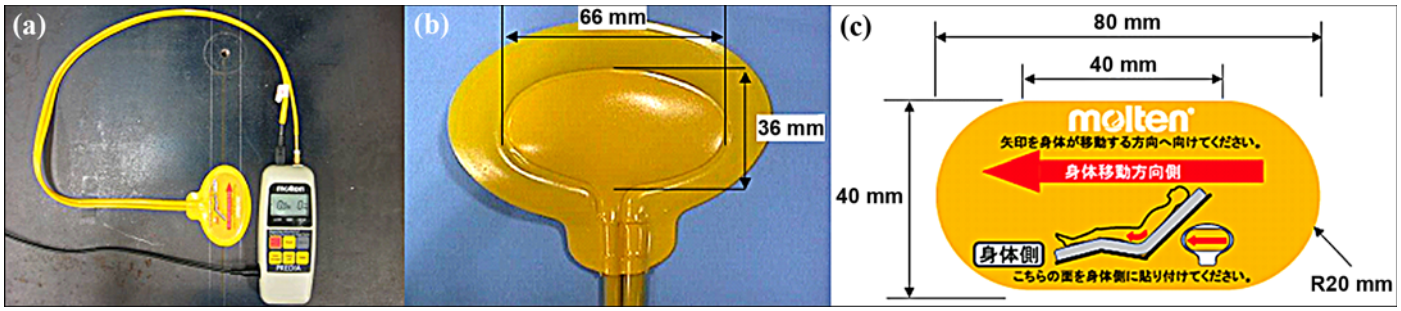

Figure 2.
Predia (Molton Corp; Hiroshima, Japan) pressure and shear force sensor shown **(a)** assembled and with **(b)** dimensions for pressure sensing area and **(c)** dimensions for shear sensing area.

Sensor Validation

Accuracy of pressure and shear measurements from the sensor was quantified in terms of bias and precision [16]. Measurement bias was assessed by determining the average difference between the measured pressure and shear values and the accepted reference values. Precision was assessed by determining the standard deviation of the difference between the measured pressure and shear values and the accepted reference values. Reliability of the sensor was quantified using intraclass correlation coefficients (ICCs) of pre- and posttesting measurements.

Pressure and shear validity were measured by applying known weight and horizontal force, respectively. Pressure was assessed by applying five loads (8.1, 43.0, 86.0, 129.0, and 172.0 mmHg) to the sensor that covered the range of the sensor (0–200 mmHg). The applied loads were used as the accepted reference values for pressure. Shear was assessed by applying a pressure of 172 mmHg to the sensor, then applying four displacements (5, 10, 15, and 20 mm). The resulting force from the load cell was considered the accepted reference value for shear and was compared with the shear measurement from the sensor. Pressure and shear measurements were recorded 3 seconds after the pressure/shear was applied. Pre- and posttest measurements were used to calculate ICCs using a two-way random effects model (ICC[2,k]).

Protocol

The protocol chosen for this study was a modified "Lateral and Forward Stiffness" test from "Annex C" of ISO 16840-2 [14]. ISO 16840-2 specifies that one horizontal displacement (10 mm) be applied to the RCLI, with the resulting horizontal force recorded after 60 seconds. Using a modified procedure, we applied multiple horizontal displacements (0, 10, 15, 20 mm) and recorded the resulting horizontal force after 60 seconds. The rationale for additional horizontal displacements was to calculate an actual stiffness variable from the slope of the resulting force-displacement curve. Actual stiffness cannot be calculated with a single force measurement.

The protocol consisted of preconditioning and testing phases. For preconditioning, cushions were acclimated to target test environment of 23 ± 2 ºC and 50 ± 5 percent relative humidity for 12 hours and adjusted to accommodate an 830 ± 10 N (84.7 ± 1.0 kg) load, if applicable. The preconditioning phase consisted of two load/unload cycles. Each cycle consisted of an 830 ± 10 N (84.7 ± 1.0 kg) load applied for 150 seconds with the RCLI and a recovery period of 120 seconds. After preconditioning, cushions were allowed a recovery time of a minimum of 5 minutes and a maximum of 60 minutes. Cushions were then adjusted to accommodate a 500 ± 10 N (51.0 ± 1.0 kg) load and the cushion material reset, if applicable. Cushions were positioned under the RCLI such that the ITs of the indenter were 125 ± 25 mm forward of the back edge of the cushion or aligned with the cushion feature designed to accommodate the ITs. The testing phase consisted of five trials each of four horizontal RCLI displacements of 0, 10, 15, and 20 mm. A vertical load of 500 ± 10 N (51.0 ± 1.0 kg) was applied to the cushion via the RCLI. Within 60 ± 5 seconds, a horizontal RCLI displacement was applied at a rate of 2 ± 1 mm/s and held for 60 seconds. The cushion was unloaded, material was reset, and the cushion was reloaded within 120 seconds.

Data Analysis and Reduction

Interface pressure, interface shear force, horizontal force, and horizontal RCLI displacements were recorded

for each RCLI displacement after 60 seconds. Mean horizontal force and interface shear force measurements were used with horizontal RCLI displacements (0, 10, 15, and 20 mm) to construct force-displacement and shear-force-displacement curves, respectively. A regression analysis of the force-displacement and shear-force-displacement curves resulted in overall horizontal stiffness and local horizontal stiffness, respectively. Overall horizontal stiffness was defined as the cushion's ability to resist a tangentially applied force, and local horizontal stiffness was defined as the cushion's ability to locally resist a tangentially applied force. Since many cushions are composed of a combination of materials, a local value of stiffness was warranted. ISO 16840-2 stiffness was calculated per the standard as the mean horizontal force measured at 10 mm horizontal displacement after 60 seconds.

Statistical Analysis

Kruskal-Wallis tests were performed to determine whether interface shear stress and interface pressure increased with applied displacement ($\alpha = 0.05$). Cushions were then categorized into groups based on the materials of construction: viscous fluid ($n = 5$), air cell ($n = 7$), elastic/viscoelastic (VE) foam ($n = 6$), and honeycomb ($n = 3$). Kruskal-Wallis tests were performed to determine whether material of construction significantly changed interface shear stress, interface pressure, or horizontal stiffness measurements ($\alpha = 0.05$). Nonparametric tests were chosen because of violations of equal variance.

To determine whether relationships existed between interface shear stress and horizontal stiffness of cushions, we calculated Pearson product moment correlation coefficients ($\alpha = 0.05$). Specifically, correlation coefficients were calculated between mean interface shear stress and overall horizontal stiffness, mean horizontal force and local horizontal stiffness, overall horizontal stiffness and ISO 16840-2 stiffness, and local horizontal stiffness and ISO 16840-2 stiffness. All statistics were analyzed with SPSS statistical software (SPSS, Inc; Chicago, Illinois).

RESULTS

Sensor Validation

Measurement bias and precision were calculated for pre- and posttest data (**Table 2**). Due to the large measurement bias for pressure, a calibration curve was constructed. The calibration curve was a plot of the measured pressure versus the accepted reference value, and a second order polynomial regression line was fitted. The regression equation was used to calculate corrected pressure data. Pressure resulted in excellent reliability (ICC = 0.993), and shear resulted in good reliability (ICC = 0.885).

Interface Shear Stress

Two elastic foam cushions were excluded from all analyses because shear sensor saturation (50 N) occurred. Interface shear stress ranged from 0.8 to 14.9 kPa, increased significantly with applied displacement ($p < 0.001$) (**Figure 3(a)**), and differed significantly by material of construction for all displacements ($p < 0.03$). Mann-Whitney *U*-tests were performed to determine the location of the significant differences using a Bonferroni correction ($\alpha = 0.05/4 = 0.013$). At 0-mm displacement, only viscous fluid and elastic/VE foam were significantly different ($p = 0.001$). Interface shear stress was significantly different for all materials of construction at 10, 15, and 20 mm displacements ($p < 0.006$), with the exception of air cell and elastic/VE foam for displacements of 10 ($p = 0.08$) and 15 mm ($p = 0.03$).

Interface Pressure

Interface pressure ranged from 8 to 78 mmHg, did not increase significantly with applied displacement ($p = 0.09$), and differed significantly by material of construction for all displacements ($p < 0.001$) (**Figure 3(b)**). Mann-Whitney *U*-tests ($\alpha = 0.013$) resulted in significantly different interface pressure for all materials of construction ($p < 0.001$), except viscous fluid and elastic/VE foam for all displacements ($p = 0.18–0.42$).

Table 2.
Measurement bias and precision of pressure and shear force sensor (data presented as mean ± standard deviation).

Measurement	Measurement Bias			Measurement Precision		
	Pre	Post	Average	Pre	Post	Average
Pressure (mmHg)	20.46 ± 23.10	20.00 ± 27.60	—	3.25 ± 2.60	2.50 ± 1.20	—
Corrected Pressure (mmHg)	–1.21 ± 4.50	0.58 ± 4.42	–0.32 ± 4.46	6.83 ± 6.58	3.73 ± 1.81	5.28 ± 4.20
Shear (kPa)	–2.60 ± 5.11	0.64 ± 2.73	–0.98 ± 3.92	0.83 ± 0.36	0.37 ± 0.26	0.60 ± 0.31

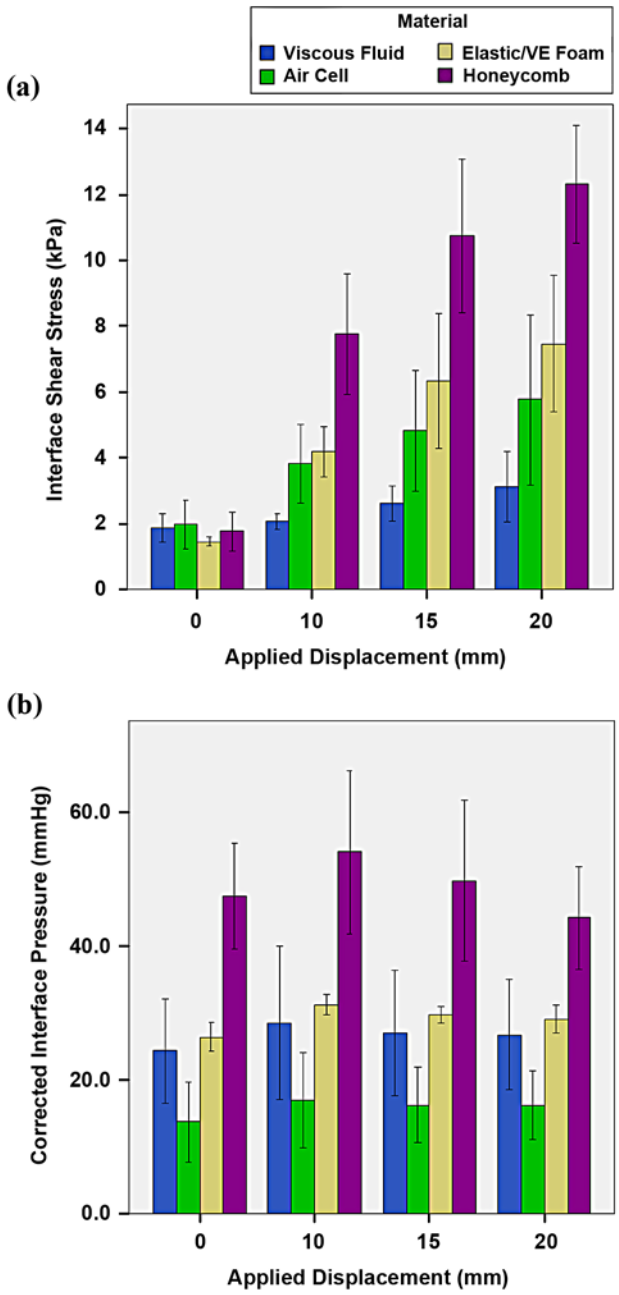

Figure 3.
Results of **(a)** interface shear stress and **(b)** interface pressure across applied displacement (0, 10, 15, 20 mm) by material of construction: viscous fluid (n = 5), air cell (n = 7), elastic/VE foam (n = 4), and honeycomb (n = 3). Interface shear stress increased significantly across applied displacement ($p \leq 0.001$) and interface pressure did not ($p = 0.09$). VE = viscoelastic.

Horizontal Stiffness

Overall horizontal stiffness and ISO 16840-2 stiffness were not significantly different between material of construction ($p = 0.29$ and $p = 0.14$, respectively) and their results were similar (**Figure 4**). Local horizontal stiffness was significantly different for material of construction ($p = 0.007$), and Mann-Whitney U-tests were performed to determine the location of the significant difference ($\alpha = 0.013$). While the Bonferroni corrected alpha level failed to find a significant difference ($p > 0.013$), viscous fluid and elastic/VE foam ($p = 0.014$) and air cell and honeycomb ($p = 0.017$) were nearly significantly different.

Significant positive relationships were found between local horizontal stiffness and horizontal force ($r = 0.49$ and $r = 0.51$, respectively); however, no significant correlations were found between interface shear stress and overall horizontal stiffness ($0.09 < r < 0.35$) as shown in **Table 3**. A positive correlation was found between overall horizontal stiffness and local horizontal stiffness, and significant positive correlations were found between overall and local stiffness values and ISO 16840-2 stiffness ($r = 0.95$ and $r = 0.51$, respectively), as shown in **Table 4**.

DISCUSSION

Pressure and shear are the mechanical extrinsic risk factors known to increase the risk of pressure ulcers [5]. Pressure mapping has allowed quantification of interface pressure and a visual representation of real-time pressure redistribution. Clinicians have incorporated the pressure mapping tool to aid in the decision-making process of cushion prescriptions. This was the first study to quantify interface shear stress of commercial wheelchair seat cushions and provides clinicians additional information about a cushion's response to horizontal displacement.

Sensor Validation

The pressure and shear force sensor used in this study was used in previous studies [17–21], and the shear force measurement error was established as ±1 N by Nakagami et al., Okazaki et al., and Okubo et al. [17,20–21] and 2.7 N by Oduncu and Melhuish [18]. Measurement bias of shear force was –2.8 N (–0.98 kPa), and precision was 1.7 N (0.60 kPa). The greater error observed in this study may be due to a larger range of measured shear force. The largest range of shear force in previous studies was from 0 to 11.7 N [17] compared with 0 to 41.9 N (0.8–14.9 kPa) in this study. In the previous studies, the sensor was adhered to a flat, rigid surface and different wound dressings were

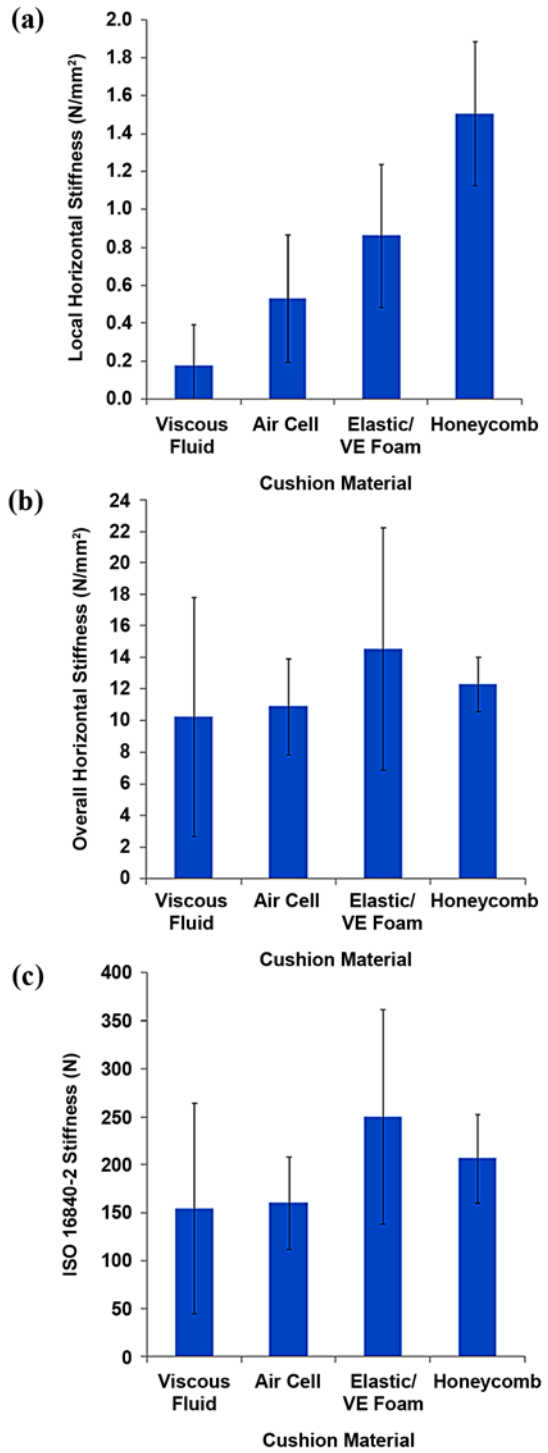

Figure 4.
Horizontal stiffness by material of construction: viscous fluid ($n = 5$), air cell ($n = 7$), elastic/VE foam ($n = 4$), and honeycomb ($n = 3$). **(a)** Local horizontal stiffness was significantly different by material of construction ($p = 0.007$) and no significant difference was found for **(b)** overall horizontal stiffness ($p = 0.29$) or **(c)** International Organization for Standardization (ISO) 16840-2 stiffness ($p = 0.14$). VE = viscoelastic.

Table 3.
Correlation coefficients (r) for forces and horizontal stiffness values.

Force	RCLI Displacement (mm)	Overall Horizontal Stiffness	Local Horizontal Stiffness
Interface Shear Stress	10	0.09	—
	15	0.33	—
	20	0.35	—
Horizontal Force	10	—	0.51*
	15	—	0.49*
	20	—	0.43

*Correlation significant at 0.05 level.
RCLI = rigid cushion loading indenter.

Table 4.
Correlation coefficients (r) for horizontal stiffness values.

Stiffness	Overall Horizontal Stiffness	Local Horizontal Stiffness	ISO 16840-2 Stiffness
Overall Horizontal Stiffness	1	0.43	0.95*
Local Horizontal Stiffness	—	1	0.51†
ISO 16840-2 Stiffness	—	—	1

*Correlation significant at 0.01 level.
†Correlation significant at 0.05 level.
ISO = International Organization for Standardization.

evaluated by applying a horizontal displacement across the static sensor [17,19]. In this study, the sensor was also adhered to a flat, rigid surface, but the surface and sensor were moved with respect to a static cushion, potentially causing greater error. Establishing bias and precision of the Predia pressure and shear force sensor will allow future researchers to use the sensor with confidence.

Interface Shear Stress and Pressure

Bennett et al. and Goossens et al. previously measured interface shear stress of rigid plastic (0.9–2.6 kPa) [11–12], wood (4.6–9.6 kPa) [22], foam (6.5–6.8 kPa) [23], gel (4.4–6.4 kPa) [22–23], and a LiquiCell (LiquiCell Technologies, Inc; Eden Prairie, Minnesota) overlay (4.0–4.8 kPa) [23]. In this study, interface shear stress ranged from 0.8 to 14.9 kPa. The greater amount of interface shear stress measured in this study was most likely due to a different sensor and the RCLI. The difficulty in obtaining interface shear stress measurements has simply been the lack of sensors capable of such measurements. Bennett et al. noted that the sensor used in their study would register less than the true value of local shear because dissimilar materials were in contact with the

sensor and the sensor was located 2 to 3 cm lateral of the IT [10]. The sensor used by Goossens et al. was not completely validated [22], which could be a reason for the greater values in this study. Measurements obtained by all sensors were on the same order of magnitude, and the primary advantage of the sensor used in this study is that it is commercially available. The RCLI is made of fiberglass and would likely create larger interface shear stresses than soft tissues because fiberglass is not compliant.

Interface pressure of cushions has been evaluated previously on foam, air, gel, and powered alternating cushions [6–7]. Mean interface pressures ranged from 6.13 to 20.93 kPa (46–157 mmHg), and peak interface pressures saturated the sensor at 26.66 kPa (200 mmHg). In this study, mean interface pressure ranged from 1.07 to 10.40 kPa (8–78 mmHg). The discrepancy between the previous studies and this study is most likely due to the method of force application and sensor placement. Forces were applied to cushions using humans in the previous studies, and an RCLI was used in this study. Variations between humans and the RCLI include rigidity, size, and shape. The sensor was placed just anterior to the left IT of the RCLI and provided a flat, rigid surface. Placing the sensor directly on the IT resulted in bending of the sensor, and pilot data indicated that this bending resulted in erroneous pressure and shear force measurements. Therefore, the sensor was moved just anterior to the IT because the surface was flat.

Interface shear stress was significantly different for all materials of construction, except air cell and elastic/VE foam at 10 and 15 mm, and increased significantly with increased displacement. Interface shear stress is a measure of a cushion's ability to absorb applied displacements without transferring shearing force to soft tissues. Viscous fluid resulted in the least amount of interface shear stress followed by air cell, elastic/VE foam, and honeycomb. These differences were more evident at higher displacements. Animal studies have demonstrated that shearing forces increase severity of pressure ulcers and decrease cutaneous blood flow [8–9]. Future research should focus on establishing a threshold for an acceptable level of interface shear stress at bony prominences. Interface pressure varied significantly for all materials of construction, except viscous fluid and elastic/VE foam, and did not increase with increased displacement. Air cell cushions had the lowest interface pressure followed by viscous fluid, elastic/VE foam, and honeycomb. Lower interface pressure is associated with reduced risk of pressure ulcer development [6].

Horizontal Stiffness

In a previous study, horizontal stiffness was collected for 21 wheelchair seat cushions using the "Lateral and Forward Stiffness" test protocol from "Annex C" of ISO 16840-2 [24]. The same protocol was used to determine horizontal stiffness as in this study except that only one displacement (10 mm) was used. The horizontal stiffness measurements ranged from 80 to 325 N compared with 92 to 403 N in this study (recorded at 10 mm displacement). The reason for greater values measured in this study was likely the method of securing the cushion during testing. In the previous study, the cushion was adhered to a scale [24] compared with a rigid base in this study. The scale was designed with flexible plastic tabs at each corner to stabilize a platform and possibly absorbed a portion of the horizontal force, resulting in lower measurements.

Our rationale for using the horizontal stiffness measurement was that it relates to the amount of shear stress imparted by the cushion to the patient's soft tissue. The higher the horizontal stiffness, the higher the shear stress. Overall horizontal stiffness and ISO 16840-2 stiffness resulted in similar results when grouped by material of construction, and neither measure differentiated cushions by material of construction. Elastic/VE foam had the largest stiffnesses and viscous fluid, air cell, and honeycomb were similar ($p > 0.14$). In contrast, local horizontal stiffness was significantly different by material of construction ($p = 0.007$). The trend in local horizontal stiffness values was the same as for interface shear stress; viscous fluid resulted in the least amount of local horizontal stiffness followed by air cell, elastic/VE foam, and honeycomb. Additionally, no significant relationship was noted between interface shear stress and overall horizontal stiffness ($0.08 < r < 0.35$). These results indicate that testing the overall horizontal stiffness of a cushion does not provide information about the cushion's ability to reduce interface shear stress at the IT.

The high correlation between ISO 16840-2 stiffness and overall horizontal stiffness ($r = 0.95$) shows that the current horizontal stiffness test methodology ("Annex C" of ISO 16840-2) provides sufficient information about overall horizontal cushion stiffness. The single displacement used to calculate ISO 16840-2 stiffness requires less testing, data processing, and data analysis. Due to the lack of a relationship between interface shear stress and overall horizontal stiffness, a pressure and shear force sensor should be used with ISO 16840-2 stiffness to fully quantify a cushion's ability to reduce interface shear at the patient's bony prominences.

Limitations

Limitations exist in our ability to compare values in this study with those from previous studies because of the use of different shear sensors and potential erroneous forces created by the sensor itself. Shear sensors used in previous studies were not available for this study and are not commercially available. Placement of the sensor in between the RCLI and the cushion surface changes the actual contact conditions and may introduce forces that are not normally present; however, this limitation will be inherent with any sensor. Another limitation of this study was the inability to control relative humidity during testing. ISO 16840-2 required a relative humidity of 50 ± 5 per cent, and we were unable to maintain this range during testing. Fluctuations in relative humidity may result in different shear force measurements because of changes in the coefficient of friction. Future studies should investigate the variation in the coefficient of friction due to changes in relative humidity and microclimate.

CONCLUSIONS

This study quantified interface shear stress, interface pressure, and horizontal stiffness for commercial wheelchair seat cushions and determined whether a relationship existed between interface shear stress and horizontal stiffness of cushions. Cushions were grouped by material of construction, and we found that interface shear stress increased significantly with increased displacement. Viscous fluid cushions resulted in the least amount of interface shear stress followed by air cell, elastic/VE foam, and honeycomb. These differences were more evident at higher displacements. No significant differences in interface pressure were found with increased displacement. The high correlation between ISO 16840-2 stiffness and overall horizontal stiffness indicates that the current horizontal stiffness test methodology ("Annex C" of ISO 16840-2) provides sufficient information about overall horizontal cushion stiffness. However, these measures do not provide information about the cushion's ability to reduce interface shear stress at the patient's IT, and an interface shear stress sensor may aid clinicians in their cushion selection.

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Author Contributions:
Study concept and design: J. S. Akins, D. M. Brienza, P. E. Karg.
Acquisition of data: J. S. Akins.
Analysis and interpretation of data: J. S. Akins, D. M. Brienza, P. E. Karg.
Drafting of manuscript: J. S. Akins.
Critical revision of manuscript for important intellectual content: J. S. Akins, D. M. Brienza, P. E. Karg.
Statistical analysis: J. S. Akins.
Obtained funding: J. S. Akins, D. M. Brienza.
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Study supervision: D. M. Brienza.
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