HUMAN AND TEST BAG IMPACT LOADS ON STATIONARY SEATING

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Abstract. Human subjects were hired to sit on an instrumented chair to measure impact loading as a function of time. These loads were compared with testing loads that are used in the ANSI/BIFMA X5.4 and X5.1 Seat drop and seat durability loading test regimens. Factors that were investigated experimentally on impact loading were standing-to-sitting ingress[1] motion, seat foundation type, seat height, as well as sandbag weight and drop height. Center of seat deflection, caused by human subjects and sandbags, were recorded as a function of time. Experimental results from human subjects' sitting tests concluded that maximum sitting forces averaged 100% and 247% with respect to a participant's body weight for normal and maximum sitting impact forces. The seat deflection speeds for normal sitting was 16.3 cm/s and varied from 71 to 84 cm/s for hard sitting. Sandbag free drop experimental results indicated that drop height had a significant effect on maximum impact forces on the seat foundations. Maximum impact drop forces increased as sandbag weight increased, but the significance was dependent on the seat foundation type. The panel-foam seat foundation had the lowest impact force among three seat foundations evaluated. The spring-foam seat foundation resulted in significantly higher impact forces than the panel-only seat foundation if the sandbag drop height was less than 13 mm, but as the drop height increased to 30 mm,

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[1] For the purposes of this paper, ingress refers to the entrance of the sitter into the seat, and subsequent movement associated with that ingress until its residual effects dampen out.

the significance became less. The impact force on a panel-only seat foundation became significantly higher than the spring-foam foundation as the drop height increased to 50 mm.

Keywords: Seat foundation, seat stiffness, sitting force, ingress, seat impact loading, seat deflection speed.

INTRODUCTION

Safety and durability design and testing of seating require engineering information related to sitting forces applied to a seat foundation during human daily sitting activities. Literature relating to the dynamic effects of human subjects' ingress on sitting forces was limited, especially ingress motion, which can significantly alter the magnitude of a sitting force applied to a seat.

Most sitting force studies focused mainly on static sitting. Hu et al (2015) reviewed previous studies related to sitting forces in terms of percentages as related to the participants' body weights and found that the percentage value of impact forces under normal ingress varies from 38% to 95% for participant weighing less than 83 kg. The wide variation of the percentage seems to be because of ingress motion causing different seat deflection speeds, or other factors such as seat foundation stiffness, seat height, and participants' weights. Paoliello and Carrasco (2008) reported a percentage of 205 when participants who weighed 69 kg sat hard on a chair. Hu et al (2015) reported that hard ingress sitting impacts of participants who weighed from 136 to 186 kg yielded at most, 213%, whereas the normal ingress impact force yielded an average percentage of 108. However, there was no seat deflection speed reported in these human subjects' sitting force studies to reflect the human subjects' sitting dynamic effects.

In addition, there was no literature discussing the variation of an actual impact load applied to a tested seat using a sandbag as is used with the testing load in ANSI/BIFMA X-2012. Current seat testing standards such as general-purpose office chair-tests (ANSI/BIFMA X-2011) and lounge and public seating (BIFMA X5.4-2012) use 115 kg, which is the 95th percentile male weight based on the CAESAR anthropometric database, as this weight is the targeted testing load.

The main objective of this study was to investigate maximum impact forces applied to seating when subjected to typical loads during all phases of a human subject ingress or a sandbag free drop. The specific objectives were to 1) measure the impact forces on seat foundations subjected to loads from human subjects' sitting forces and sandbag free drop forces; 2) investigate the effects of human subject ingress motion, seat foundation type, and seat height on the maximum impact sitting forces on seat foundations; and 3) evaluate the effects of sandbag weight and drop height on the magnitude of impact forces on seat foundations, with different stiffness properties. Furniture testing standards have been evolving as more research has been available, resulting in improved testing procedures over time. This research is part of the continuing effort to increase and improve the body of knowledge in this area. This allows testing procedures to be refined so that manufacturers need not pass tests that are overly strenuous, or obtain a false sense of security with results of tests that are not strenuous enough. The data from this study are original and have been experimentally determined, giving standard creators better tools to enhance present standards.

MATERIALS AND METHODS

Participants

There were seven healthy human subjects (four males and three females) participating in the experiment. Table 1 summarizes their anthropometric

Table 1. Summary of major participants' anthropometric measurements.

Subject	Gender	Height (cm)	Popliteal (cm)	Weight (kg)
1	F	158	40.6	57
2	F	162	43.2	51
3	F	168	43.2	58
4	M	177	47.0	74
5	M	180	49.5	85
6	M	180	55.9	79
7	M	186	47.0	115

measurements. Ethical approval was given by the Mississippi State University Institutional Review Board. Written informed consents were received from all participants.

Seat Foundation

The seat foundation of a seating system, in general, consists of a seat base frame installed with springs or webbings and a seat cushion made of one to several different foams covered with fabric or leather materials. Figure 1 shows the configurations and dimensions of three seat foundations in this experiment. The first was (Fig 1a) a wooden frame with a flat rigid plywood panel as the supporting surface. The second (Fig 1b) with foam placed on its top had a similar frame size and construction but lower height. The third (Fig 1c) had five-evenly-spaced Standard Wire Gauge no. 8 springs installed as the seat support surface. The 610-mm^2 foam block measured 100 mm thick with its density of 30 kg/m^3 and 25% indentation force deflection (IFD) of 138 N.

Experimental Design

Human subjects' sitting. A complete 3 × 3 × 2 factorial experiment was conducted to evaluate the factors on impact sitting forces applied to seat foundations as a function of time and center deflections of each seat foundation top surface as a function of time during human subjects' sitting. The three factors were ingress motion (normal, hard), seat foundation type (panel-only, panel-foam, spring-foam), and seat height (−38, 0, 38 mm). A normal ingress motion was defined in this study as how one normally sits in a good manner, which happens in public, working, and official environments. A hard ingress motion was to represent a relaxed drop of the body onto a seat, which would more likely happen at home and entertainment places. The positive 38-mm seat height means that a human subject's popliteal is 38 mm higher than the seat foundation top surface (Fig 2). A 0-mm seat height means that the human subject's popliteal has the same height as the seat foundation top surface.

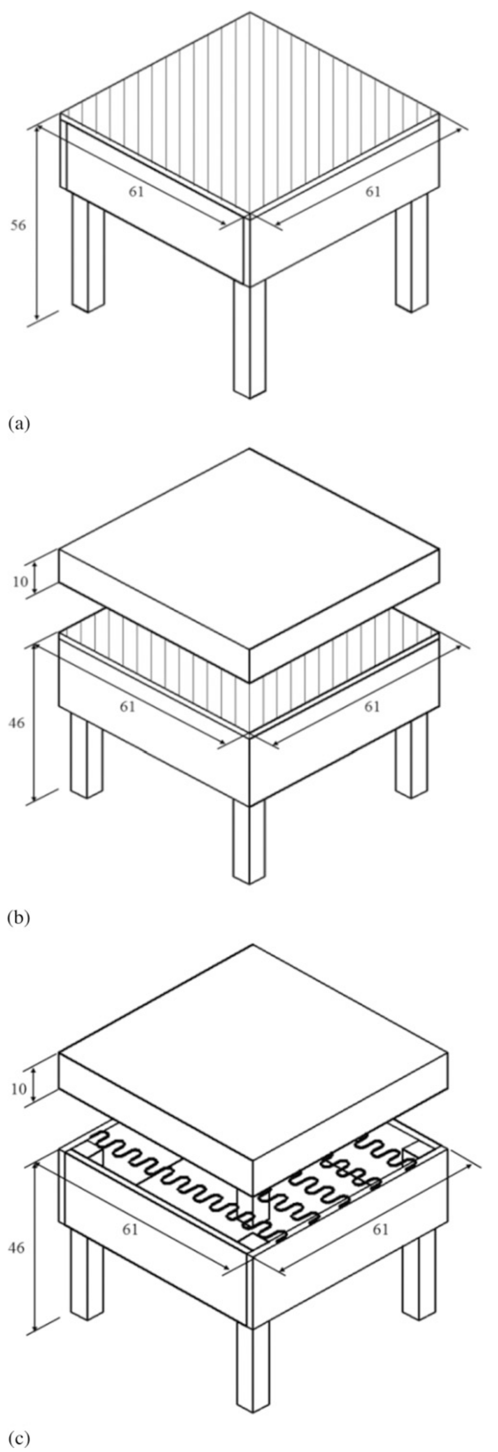


Figure 1. Seat foundation types: (a) panel top frame base, (b) panel top frame base with foam, and (c) spring top frame base with foam, and units are all in centimeters.

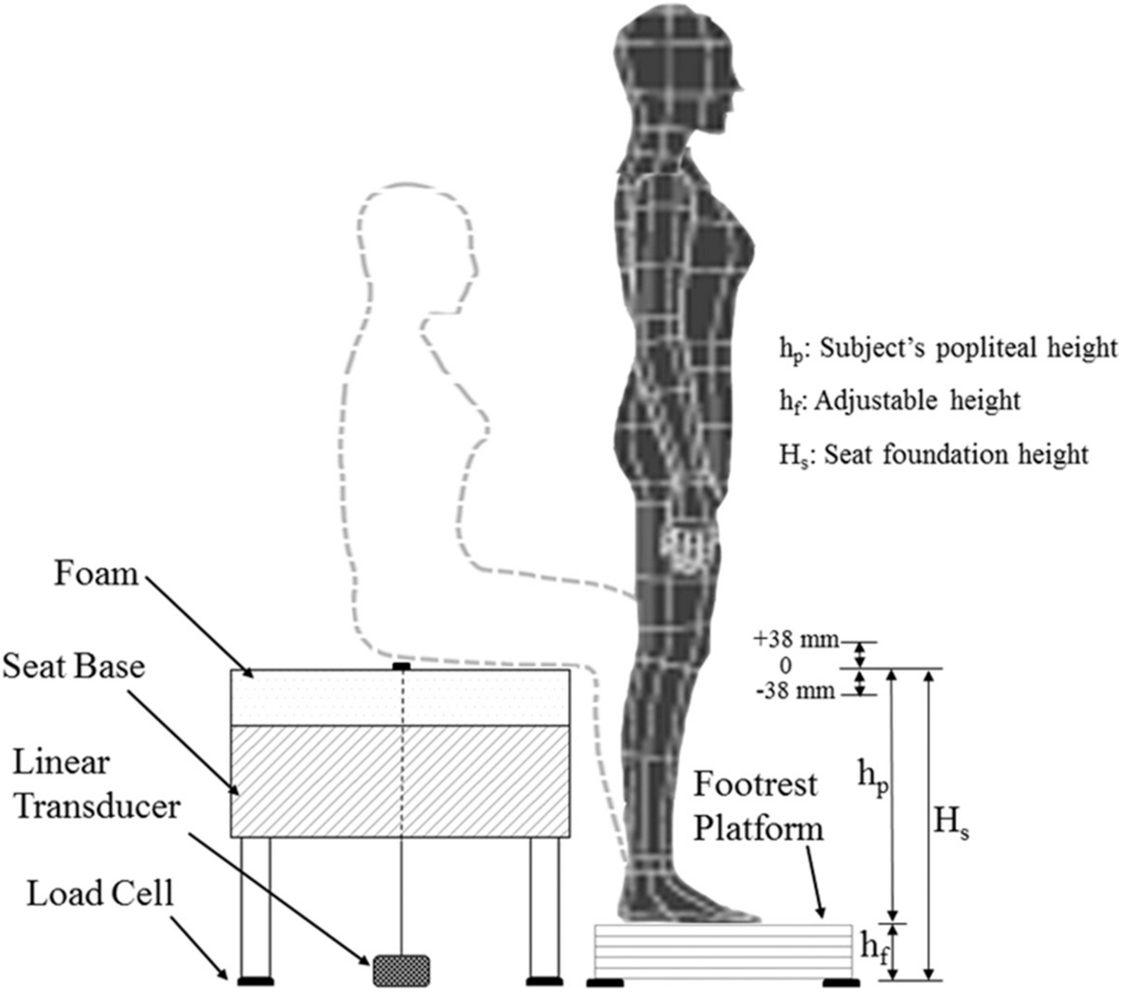


Figure 2. Setup for human subjects' sitting tests.

A negative 38-mm seat height means that a human subject's popliteal is 38 mm lower than the seat foundation top surface. Seven participants performed the sitting for each of 18 experimental combinations.

Sandbag dropping. A complete 3 × 4 × 4 factorial experiment was conducted to evaluate the factors on maximum dropping forces applied to seat foundations as a function of time and center deflections of the seat foundation top surfaces as a function of time during the sandbag free drop. The three factors were seat foundation type (panel-only, panel-foam, spring-foam), sandbag drop height (0, 13, 30, 50 mm), and sandbag weight (34, 45, 57, 68 kg). Three drops were performed in each experimental combination to consider the variation that occurred during sandbag free drops, including the sandbag weight center, bag landing location, etc. In addition, the BIFMA sandbag free drop testing procedure was performed on three seat foundations.

Testing Procedure

Figures 2 and 3 show the setups instrumented with load cells and a linear position transducer to record vertical impact forces on seat foundations

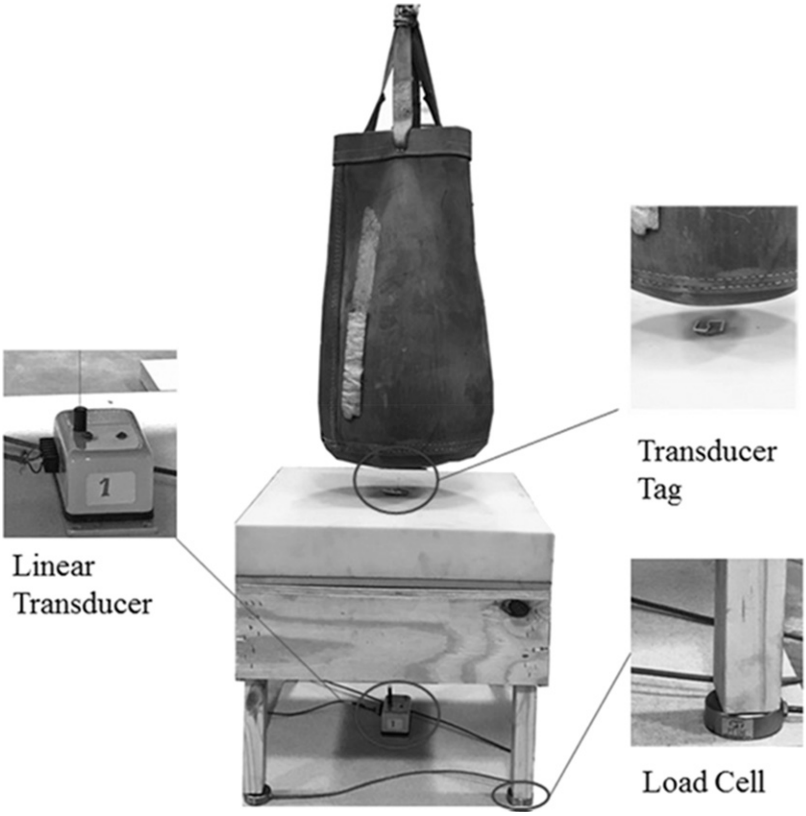


Figure 3. Setup for sandbag free drop tests.

as a function of time and their corresponding simultaneous deflections that occurred at the center of the seat foundation surface as a function of time when human subjects ingressed or sandbags were freely dropped. For each of two setups, four load cells (PT Global LPX-250 button load cells with 250-kg loading capacity, Auckland, NZ) attached to the bottoms of four seat foundation legs measured vertical impact forces. The magnitude of a vertical impact force on a seat foundation was the sum of four loading forces recorded through these four load cells. A footrest platform in front of the chair, instrumented with four PT Global LPX-250 bottom load cells (Fig 2), simultaneously measured vertical forces applied to the platform during the period of a participant sitting. A National Instruments (Austin, TX) SCXI-1000, with two 1102B modules (each using a 1303 interface) recorded the load cells' outputs used for the determination of loading forces. All force values were in kilograms for easy comparison with loading weights. The line end of a linear position transducer (Unimeasure PA-40-N20-D1S-10T, Corvvallis, OR) was attached to the top center of the foam placed on seat base frames (Figs 2 and 3) measured the center deflection of seat foundations subjected to vertical loadings.

Human sitting test. Participants' anthropometric measurements were taken at the beginning of sitting tests. An adjustable footrest (Fig 2) was used to ensure the difference between the height of the seat surface and subject's popliteal was the same for all participants. Each participant performed normal and hard sitting tasks. The load-time curve recorded during each sitting test was accepted only after its corresponding center deflection-time curve for the tested seat foundation was checked to make sure seat surface center deflection speeds were in a predefined range (Li 2017). Specifically, the seat deflection speed under normal ingress was less than 25 cm/s and the seat deflection speed under hard ingress was greater than 46 cm/s. There was no deflection recorded for the panel-only seat foundation type because it had a rigid surface compared with the other two seat foundation types.

Sandbag dropping test. The sandbag free dropping test for $3 \times 3 \times 2$ factorial experiment was performed in reference to the seating durability test standard (BIFMA 2011, 2012). A test sandbag of 406 mm diameter was attached to a manually controlled lifting device, which allowed free dropping of a sandbag to the seat foundation. A 50-mm-thick foam cushion with 25% IFD of 190 N was added to the top of the panel-only seat foundation during that test. Figure 4 shows the detailed setups for additional sandbag free drop tests performed strictly following the seating durability test standard (BIFMA 2011, 2012), especially the sandbag initial drop height (Fig 4).

Normalized maximum forces. Recorded maximum sitting forces from human subjects' sitting tests and dropping forces from sandbag free drop tests, P, kg, were all normalized to force-weight percentage (FWP), %, the percentage of their corresponding human subject body or sandbag weights, W, kg, respectively, using the following expression (Hu et al 2015):

$$\mathrm{FWP} = \frac{P}{W} \times 100\% \tag{1}$$

RESULTS AND DISCUSSION

Figures 5 and 6 show typical curves of vertical impact forces (both on the seat foundation and the footrest platform) as a function of time and center deflections of the seat foundation as a function of time recorded for human subjects' normal and hard ingress impacts, respectively. Figure 7 shows typical curves of vertical impact forces as a function of time and center deflections of seat foundations as a function of time recorded for sandbag free drop tests.

In general, there are two phases identified for vertical impact forces applied to seat foundations

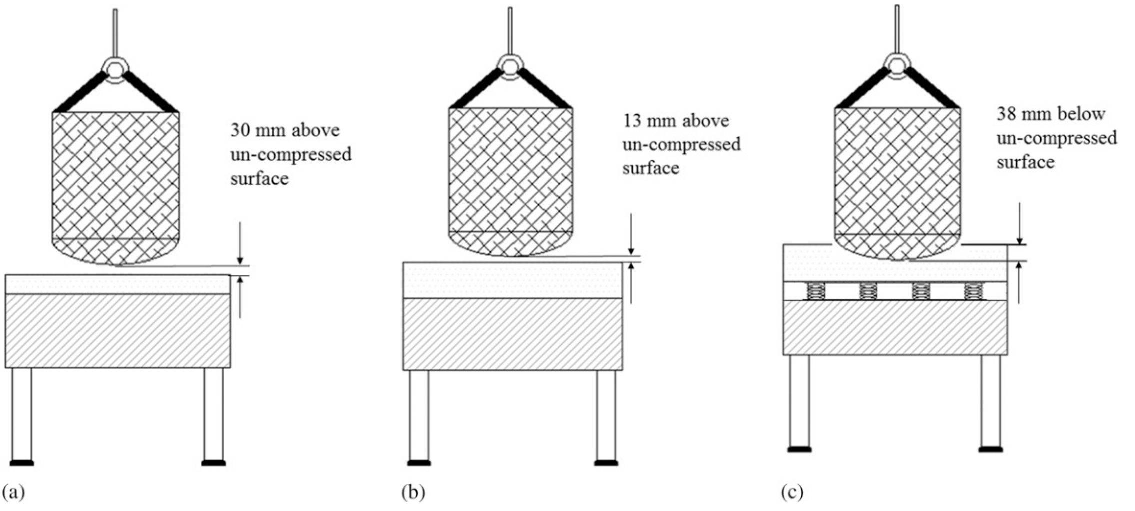
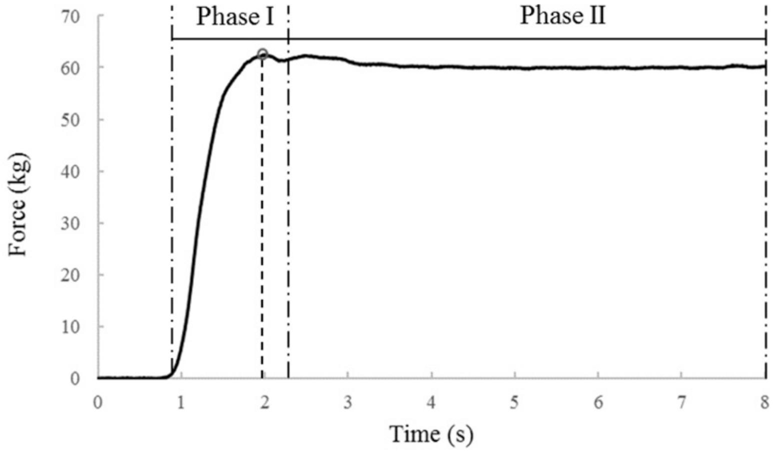
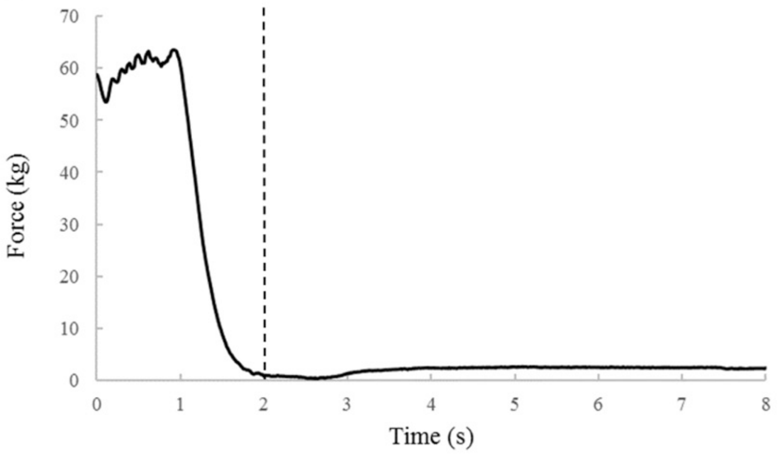


Figure 4. Setups for BIFMA sandbag drop tests: (a) 50-mm-thick foam used with sandbag 30 mm above uncompressed foam surface, (b) 100-mm-thick foam used with sandbag 13 mm above uncompressed foam surface, and (c) 100-mm-thick foam used with sandbag 38 mm compressed into foam.



(a)



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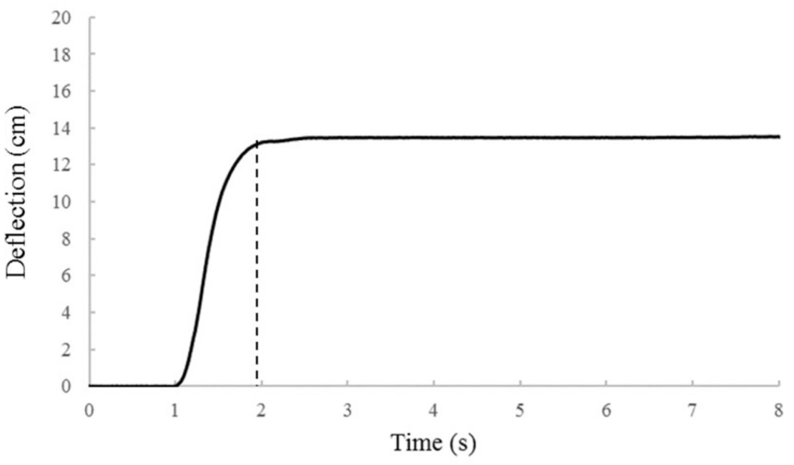


(c)

Figure 5. Typical curves of (a) impact force measured on seat foundation, (b) force measured on footrest platform, and (c) seat surface center deflection measured, as a function of time during human subjects' normal ingress.

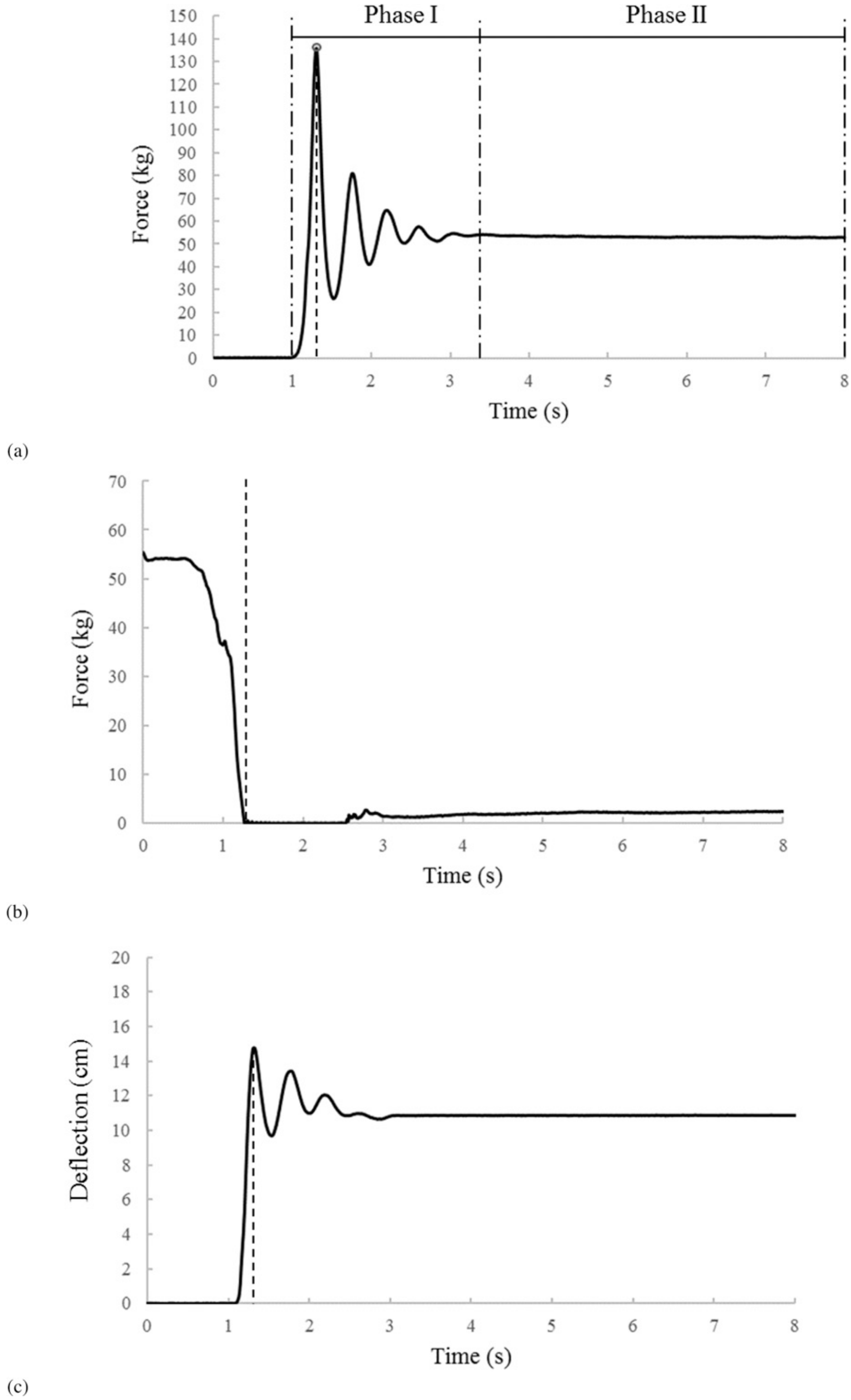
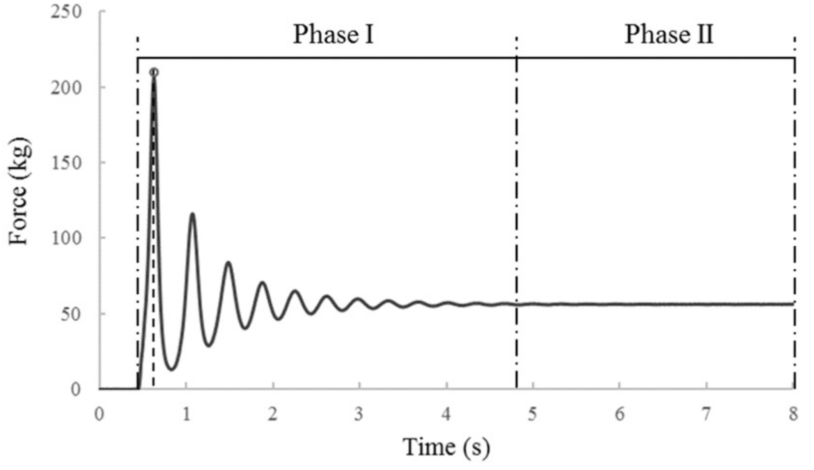
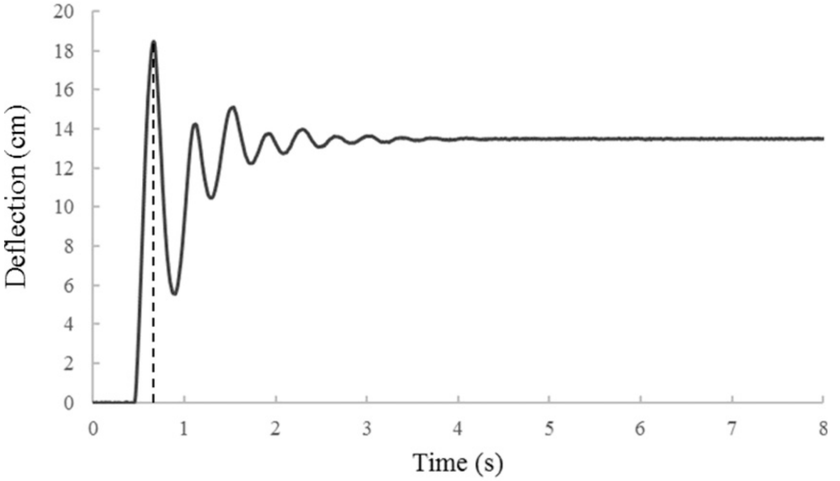


Figure 6. Typical curves of (a) impact force measured on seat foundation, (b) force measured on footrest platform, and (c) seat surface center deflection measured, as a function of time during human subjects' hard ingress.



(a)



(b)

Figure 7. Typical curves of (a) impact force measured on seat foundation and (b) seat surface center deflection measured, as a function of time during sandbag free dropping.

subjected to three different loading conditions. Phase I was the period when the loading subject began to touch the seat until the force applied to the seat reached its peak value. The peak force in Phase I was the maximum impact load applied to the seat. During the Phase II period, the vertical impact force went through a period of damping before the subject was completely seated. Figures 6a and 7a indicate that a human subjects' hard ingress impact and sandbag free drop measurements had similar force-time behaviors in Phase II, ie once the vertical impact force reached its peak value then went through a damping period, and finally became stable. This was significantly different from the normal ingress where the force had less of a damping period.

These results implied that human subjects' hard ingress impact effects were close to a free drop. The force-time curve recorded on the footrest platform (Figs 5b and 6b) represents forces sustained by the feet during a human subject's ingress. During the human subjects' hard ingress impact and the sitting force damping period, the force born by the feet became zero (Fig 6b), which indicated the human bodies were freely

Table 2. Summary of means and ranges of seat deflection speeds (cm/s) recorded during human subjects' sitting tests for each experimental combination of seat foundation type by seat height by ingress motion.[a]

	Ingress motion							
	Normal				Hard			
	Seat foundation type				Seat foundation type			
	Panel-foam		Spring-foam		Panel-foam		Spring-foam	
Seat height (mm)	Mean	Range	Mean	Range	Mean	Range	Mean	Range
+38	14 (40)	5-22	21 (4)	20-23	71 (9)	64-82	85 (23)	56-111
0	15 (34)	9-22	18 (29)	12-25	78 (22)	46-103	85 (17)	65-108
−38	13 (45)	5-22	17 (29)	12-25	64 (18)	50-81	81 (21)	59-106

[a] Value in parentheses are coefficients of variation in percentage.

dropping on the seat with feet off the ground. The force recorded on the footrest platform for human subjects' normal ingress had a nonzero force (Fig 5b), which indicated that the feet bore some body weight during normal ingressing that cannot be treated as a free drop action like a hard ingress.

Figures 5c and 6c show the center deflection of the seat surface as a function of time for the human subjects' normal and hard ingress motions, respectively. The seat deflection speed was defined as the maximum center deflection of a tested seat divided by its corresponding time from the recorded deflection-time curve. Comparing Figs 5c with 6c shows that a hard ingress yielded a much faster seat deflection speed than normal ingress.

Tables 2-4 summarize means and ranges of seat deflection speeds, impact time, and peak sitting forces in terms of FWP for human subjects' sitting tests, respectively. Table 5 summarizes mean peak dropping forces in terms of FWP for sandbag free drop tests for each experimental combination of seat foundation type by sandbag weight by sandbag drop height. The peak dropping forces in terms of FWP for the additional BIFMA sandbag drop test (Fig 4c) was 217%, which was not provided in Table 5. The detailed seat deflection speeds for sandbag drop tests were not reported here. Only selected seat deflection speeds related to 57-kg sandbag drop tests (Table 6) were reported for the purpose of comparison with human subjects' data. The seat deflection speeds of panel-only (Fig 4a), panel-foam, and spring-foam subjected to 30-mm-high sandbag drops were 63, 71, and 91 cm/s, respectively. The mean seat deflection speeds for sandbag free drop tests shown in Fig 4b and c were 59 and 44 cm/s, respectively. The speed data related to other sandbag drop tests can be found in the dissertation (Li 2017).

Mean Comparisons of Speed, Time, and Forces

In general, a three-factor analysis of variance (ANOVA) general linear model procedure was

Table 3. Mean impact time (s) for each experimental combination of seat foundation type by ingress motion by seat height in human sitting test.[a]

		Seat foundation type					
		Panel		Panel-foam		Spring-foam	
Ingress motion	Seat height (mm)	Mean	Range	Mean	Range	Mean	Range
Normal	+38	0.78 (18)	0.60-0.99	0.59 (25)	0.39-0.78	0.39 (21)	0.26-0.52
	0	0.63 (33)	0.38-0.90	0.64 (29)	0.25-0.81	0.54 (27)	0.40-0.76
	−38	0.68 (31)	0.37-0.94	0.57 (38)	0.32-0.88	0.70 (25)	0.42-0.95
Hard	+38	0.11 (7)	0.10-0.12	0.14 (16)	0.12-0.17	0.21 (26)	0.21-0.35
	0	0.12 (20)	0.09-0.16	0.17 (19)	0.14-0.23	0.24 (15)	0.19-0.28
	−38	0.14 (25)	0.09-0.19	0.23 (23)	0.17-0.32	0.29 (19)	0.15-0.31

[a] Value in parentheses are coefficients of variation in percentage.

Table 4. Summary of means and ranges of peak sitting forces (%) in terms of percentage of participants' body weight for each experimental combination of seat foundation type by seat height by ingress motion.[a]

		Ingress motion			
		Normal		Hard	
Seat foundation type	Seat height (mm)	Mean	Range	Mean	Range
Panel	−38	96 (5)	90-102	230 (20)	175-315
	0	95 (5)	90-103	252 (22)	189-324
	38	93 (6)	88-106	245 (22)	165-319
Panel-foam	−38	102 (6)	93-110	239 (19)	172-284
	0	98 (3)	94-102	263 (28)	167-363
	38	98 (6)	89-105	253 (21)	184-313
Spring-foam	−38	104 (7)	98-117	260 (19)	187-321
	0	101 (5)	94-108	242 (18)	181-303
	38	111 (7)	103-102	244 (19)	154-282

[a] Value in parentheses are coefficients of variation in percentage.

performed first for each of four dependent variables of seat deflection speed, impact time, peak sitting force, and peak dropping force to analyze main effects and their interactions, followed by mean comparisons using the protected least significant difference (LSD) multiple comparison procedure if any significant interaction was identified. All statistical analyses performed were at the 5% significance level. Table 7 summarizes ANOVA results for each of four dependent variables.

Seat deflection speed. The panel-only seat foundation type was removed from data analyses since there was no deformation data to record. ANOVA results (Table 7) indicated that all three-way and two-way interactions, and the main effect of seat height were not significant. Mean comparisons of seat deflection speeds for seat height indicated that seat height had no significant effect on seat deflection speed.

Further inspection of the magnitudes of F values for two significant main effects (Table 7) indicated

Table 5. Summary of mean vertical peak drop forces (%) in terms of percentage of sandbag weight for each experimental combination of sandbag weight by drop height by seat foundation type, and mean comparisons of vertical peak drop forces for seat foundation type.[a]

		Seat foundation type[b]		
Sandbag weight (kg)	Drop height (mm)	Panel	Panel-foam	Spring-foam
34	0	169 (9) B	157 (9) B	240 (1) A
	13	243 (2) B	193 (9) C	282 (1) A
	30	328 (3) A	243 (4) B	309 (1) A
	50	408 (3) A	283 (6) C	351 (0) B
45	0	186 (8) C	200 (6) B	250 (6) A
	13	258 (0) B	239 (1) B	299 (7) A
	30	330 (2) A	265 (1) B	328 (1) A
	50	434 (1) A	305 (5) C	371 (2) B
57	0	235 (2) B	214 (7) C	300 (8) A
	13	308 (3) B	268 (3) C	342 (7) A
	30	356 (7) A	310 (5) B	367 (4) A
	50	467 (2) A	342 (5) C	417 (3) B
68	0	246 (5) B	203 (5) C	330 (1) A
	13	334 (1) B	274 (4) C	367 (0) A
	30	411 (1) A	327 (2) B	401 (1) A
	50	514 (3) A	401 (2) C	449 (1) B

[a] Value in parentheses are coefficients of variation in percentage.
[b] Means not followed by a common letter are significantly different at the 5% level.

Table 6. Mean comparisons of peak dropping forces (%) in terms of percentage of sandbag weight for sandbag weight within each combination of seat foundation type by sandbag drop height.

Seat foundation type	Drop height (mm)	Sandbag weight (kg)[a] 34	45	57	68
Panel	0	169 B	186 B	235 A	246 A
	13	243 C	258 C	308 B	334 A
	30	328 C	330 C	356 B	411 A
	50	408 D	434 C	467 B	514 A
Panel-foam	0	157 B	200 A	214 A	203 A
	13	193 C	239 B	268 A	274 A
	30	243 C	265 B	310 A	327 A
	50	283 D	305 C	342 B	401 A
Spring-foam	0	240 C	250 C	300 B	330 A
	13	282 C	299 C	342 B	367 A
	30	309 C	328 C	367 B	401 A
	50	351 C	371 C	417 B	449 A

[a] Means not followed by a common letter are significantly different at the 5% level.

that the ingress motion had a much larger F value of 629.93 than the seat foundation type with an F value of 13.46. This means that the significance of the ingress motion effect on the seat deflection speed was much stronger than the seat foundation type. Therefore, the ingress motion effect on the seat deflection speed was performed based on mean comparisons of the main effect directly. The comparison result indicated that the hard ingress motion had a significantly faster seat deflection speed than that of the normal ingress. The effect of seat foundation type on the seat deflection speed was analyzed by considering the nonsignificant three-way interaction because the nature of conclusions from interpretation of main effects also depends on the relative magnitudes of the interaction and individual main effects (Freund and Wilson 1997).

Table 8 shows mean comparison results of seat deflection speeds for each seat foundation type, which were based on a one-way classification created with 12 treatment combinations with respect to the three-factor interaction and mean comparisons among these combinations using a single LSD value of 12 cm/s. In addition, mean comparisons of seat deflection speeds based on the three-way interaction for ingress motion and seat height yielded the same results obtained from mean comparison with respect to the two main effects.

Table 8 indicates that for normal ingressing, the seat foundation type had no significant effect

Table 7. Summary of analysis of variance results from general linear model procedure performed on three factors for peak sitting forces and seat deflection speed of human subject sitting tests and peak drop forces of sandbag drop tests.

	Loading type								
	Human subject						Sandbag		
	Force		Speed		Time		Force		
Source	F value	P value	F value	P value	F value	P value	Source	F value	P value
Seat	0.66	0.5199	13.46	0.0005	0.32	0.7234	Seat	528.59	<0.0001
Motion	502.09	<0.0001	629.93	<0.0001	371.65	<0.0001	Weight	383.98	<0.0001
Seat × motion	0.15	0.8644	2.53	0.1160	12.98	<0.0001	Seat × weight	3.52	0.0034
Height	0.09	0.9112	1.47	0.2366	2.60	0.0787	Height	1274.42	<0.0001
Seat × height	0.36	0.8348	0.62	0.5392	3.60	0.0086	Seat × height	75.61	<0.0001
Motion × height	0.26	0.7734	0.72	0.4883	0.00	0.9968	Weight × height	4.6	0.0001
Seat × motion × height	0.46	0.7660	0.26	0.7724	2.81	0.0292	Seat × weight × height	2.27	0.0056

Table 8. Mean comparisons of seat deflection speeds for seat foundation type within each combination of seat height by ingress motion.

		Seat foundation type[a]	
		Panel-foam	Spring-foam
Seat height (mm)	Ingress motion	cm/s	
−38	Hard	64 B	81 A
	Normal	13 A	17 A
0	Hard	78 A	85 A
	Normal	15 A	18 A
38	Hard	71 B	85 A
	Normal	14 A	21 A

[a] Means not followed by a common letter are significantly different at the 5% level.

on seat deflection speed, even though the seat deflection speeds of spring-foam seat foundations tended to be faster than the ones for panel-foam foundations. But for hard sitting situations, the seat deflection speeds of a spring-foam seat foundation were significantly faster than the ones for a panel-foam seat foundation when seat height either was lower or higher than 0-mm seat height. The seat deflection speed of a spring-foam seat foundation was faster than a panel-foam seat foundation when the seat height was 0 mm, but it was not significant.

Summarizing results related to normal ingress motion indicated that seat height and seat foundation type had no significant effect on seat deflection speeds. Therefore, averaging all six mean speeds within normal ingress motion (Table 2) yielded to 16.3 cm/s, which represents the seat deflection speed measured for human subjects' normal ingress motion evaluated in this study.

For hard ingress motions, averaging three mean speeds per sitter under panel-foam (Table 2) yielded 71 cm/s, which represents the seat deflection speed measured for human subjects' hard ingress on a panel-foam seat foundation because seat height had no significant effect on seat deflection speeds. Averaging three mean seat deflection speeds per sitter under spring-foam yielded 84 cm/s for hard ingress on a spring-foam seat foundation. Comparing seat deflection speeds of human subjects' hard ingress with sandbag free drops can yield a conclusion that a hard ingress motion can be considered as a free drop of the body drop onto a seat.

Impact time. ANOVA results (Table 7) indicate that the three-way interaction was marginally significant. Therefore, a one-way classification created with 18 treatment combinations with respect to the three-way interaction was to compare means among these combinations using a single LSD value of 0.13 s. Mean comparisons of impact time for the ingress motion indicate that the hard ingress motion had a significantly shorter impact time than normal ingress.

Peak sitting forces. ANOVA results (Table 7) indicate that all three-way and two-way interactions were not significant. Therefore, main effects on peak sitting forces in terms of the percentage of human subjects' body weight, FWP, were analyzed further. Mean comparisons of main effects indicate that the mean FWP of the hard ingress motion was significantly higher than that of normal ingress. This is mainly because the impact time measured during the hard ingress of a participant was significantly shorter than the normal ingress. This resulted in a higher impact load for hard ingress than normal ingress (Hu et al 2015). In addition, the seat deflection speed of the hard ingress motion was significantly faster than the one for normal ingress, which will also yield a higher impact force for the hard ingress motion than the normal one.

There were no significant differences among the three means of FWP values for different seat foundation types and seat heights. This indicates that seat height and seat foundation type evaluated in this study had no significant effects on FWP. No differences in peak sitting forces between seats with and without foam were because of psychological reasons. When participants saw a seat with no foam and thought the surface could be hard, they tended to restrain their descent more with their legs, ie legs tended to hold more weight during ingress motion (Li 2017). This led to less impact load on the seat foundation.

The overall averaged FWP values were 100% and 247% for normal and hard ingress motions, respectively. Hu et al (2015) indicated that the hard ingress of participants who weighed from 136 to 186 kg yielded the highest FWP of 213%, whereas normal ingress yielded an FWP value of 108%. Paoliello and Carrasco (2008) reported an FWP value of 205% when participants who weighted 69 kg sat hard onto a chair. In addition, Hu et al (2015) in their literature review found that, in general, FWP values with normal ingress vary from 38% to 95% for participants with weights less than 83 kg, and the significant variation observed in FWP values is mainly because the sitting speed was not well controlled. These results imply that the actual cycling testing load for evaluation of a seat foundation should produce a force at least 100% of human body weight, or could be up to 247% of human body weight in a worst-case scenario.

If the standard for Lounge and Public Seating Tests (BIFMA 2012) is reviewed, it can be found that the 95th percentile male weight of 115 kg is considered as human body weight for the determination of testing loads on a seat foundation. Based on previously discussed FWP results from human subject sitting tests, the following forces could possibly act on a seat foundation. If considering normal seat ingress impact, 100% of a 115-kg human body weight will yield a 115-kg force on a seat foundation. If a hard ingress impact is considered, 247% of 115 kg can yield a 284-kg force on a seat foundation.

Peak dropping forces. ANOVA results (Table 7) indicated that the three-way interaction was significant. This suggested that further analyses should focus on the significant interaction. In addition, three main effects were all significant with their P values less than 0.0001. Further checking F values of these significant main effects found that their relative magnitudes were different. Sandbag dropping height had a much greater F value of 1274.42 than seat foundation type and sandbag weight with F values of 528.59 and 383.98, respectively. Therefore, mean comparisons of main effect sandbag drop height determined its effects on the mean FWP value. Mean comparisons of sandbag drop height indicated that there were significant differences in FWP among different sandbag drop heights. Specifically, a sandbag with a 50-mm drop height yielded a significantly higher FWP value than the one with a 30-mm drop height, followed by a 13-mm drop height, then a 0-mm drop height. This is because a higher positioned sandbag has more potential energy transferred to higher impact loads on seat foundations.

The three-way interaction determined effects of seat foundation type and sandbag weight on the FWP. Tables 5 and 6 summarize mean comparisons of FWP values for seat foundation type and sandbag weight, respectively. The results were from a one-way classification created with 48 treatment combinations with respect to the three-factor interaction, and a single LSD value of 19% determines mean differences among those treatment combinations. Meanwhile, mean comparisons of FWP values for the sandbag drop height based on the LSD procedure yielded the same results from mean comparisons with respect to the main effect only.

Table 6 indicated that, in general, mean FWP values increased as sandbag weight increased, but the significance was dependent on seat foundation type and dropping height. The increase in FWP values is because a heavier sandbag has more potential energy that can convert to a higher impact force. Within each seat foundation type, mean FWP became more significant as the drop height increased from 0 to 50 mm.

Specifically, in the case of a seat foundation with panel-only, there were no significant differences in FWP values between weights of 34 and 45 kg, also 57 and 68 kg when the drop height was zero, and the significant increase in FWP values occurred as the sandbag weight increased from 45 to 57 kg. In the dropping height range from 13 to 30 mm, there was no significant increase in mean FWP values as sandbag weight increased from 34 to 45 kg. The increase in FWP became significant as the sandbag weight increased from 45 to 57 kg and from 57 to 68 kg. As the drop height increased to 50 mm, significant differences in FWP occurred among four sandbag weights.

In the case of a seat foundation with a panel-foam combination, the 34-kg sandbag had a significantly lower FWP than the other three higher weight sandbags when the dropping height was zero, and there were no significant differences in FWP among 45-, 57-, and 68-kg weights. When the drop height increased from 0 to 13 and 30 mm, significant differences in FWP occurred among 34-, 45-, and 57-kg weights, but there was no significant difference in FWP between 57- and 68-kg weights. When the drop height increased to 50 mm, there was no significant increase in mean FWP values as the sandbag weight increased from 34 to 45 kg. The increase in FWP became significant as sandbag weight increased from 45 to 57 kg and from 57 to 68 kg.

In the case of a seat foundation with a spring-foam combination, the drop height did not alter the significance of sandbag weight effects on mean FWP values. In general, there was no significant increase in mean FWP values as sandbag weight increased from 34 to 45 kg. The increase in FWP became significant as sandbag weight increased from 45 to 57 kg and from 57 to 68 kg.

Table 5 indicated that at drop heights from 0 to 13 mm, the spring-foam seat foundation had significantly higher mean FWP values than the other two supports, followed by panel-only, then panel-foam foundation. As the drop height increased to 30 mm, a significant difference in FWP between panel-foam and spring-foam foundations did not exist, but they were all significantly higher than the panel-foam foundation with respect to FWP. As the drop height increased to 50 mm, the panel-only seat foundation showed a significantly higher FWP value than the spring-foam seat foundation, followed by the panel-foam seat foundation. The main reason for the spring-foam seat foundation having significantly higher mean FWP values than the panel-foam seat foundation was that the spring-foam seat foundation yielded a larger deformation than the panel-foam seat foundation. For instance, a 57-kg sandbag free drop from 30 mm height yielded a maximum 18.2-mm deformation for the spring-foam seat foundation, but a maximum 8.8-mm deformation for the panel-foam seat foundation (Li 2017). In another words, the spring-foam seat foundation had a higher drop height yielding a higher potential energy that can be transferred into a higher impact force.

If the BIFMA test results from this study were compared, ie for a 57-kg sandbag dropping on three seat foundations following the testing procedure by considering the drop height (Fig 4), the peak dropping forces were 203 (356%), 153 (268%), and 124 (217%) kg for panel-only, panel-foam, and spring-foam seat foundations, respectively. In addition, these three drop loads were compared with some of the data listed in Table 5, for instance, a 57-kg sandbag dropping on panel-foam and spring-foam seat foundations from 30-mm height can yield peak dropping forces of 177 (310%) and 209 (367%), respectively. These results indicate that the same testing load applied to different types of tested seat foundations could produce different magnitudes of impact forces.

If these forces from BIFMA tests were compared with peak sitting forces measured from human subject's ingress tests, these three forces fall between a 115-kg force on seat foundations from normal ingress and a 284-kg force from hard ingress as previously discussed. These results imply that in real testing situations the current specified testing load could cause the force on an evaluated seat being much higher than the force occurred during the normal sitting situation, but much lower than the force occurred during real hard sitting situation.

CONCLUSIONS

Experimental results from human subjects' sitting tests concluded that the stiffness of tested seat foundations had no significant influence on seat deflection speeds when the seat was subjected to human subjects' normal ingress impact, but had significant effects on seat deflection speeds if human subjects' had hard ingress motion. The seat deflection speed under a human subject normal ingress averaged 16.3 cm/s. The seat deflection speed for human subjects' hard ingress varied from 71 to 84 cm/s, which can be viewed as a free human body drop on the seat. Recorded peak sitting forces in terms of participants' body weights averaged 100% and 247% for normal and hard ingress loads, respectively. Seat heights and seat foundation types evaluated in this study had no significant effects on peak sitting forces applied to the seat foundations subjected to human subjects' weights ranging from 51 to 115 kg.

Sandbag free drop experimental results concluded that the sandbag drop height had a significant effect on peak drop forces applied to the seat foundations evaluated in this study. In general, peak drop forces increased as sandbag weight increased, but the significance was dependent on the seat foundation type in terms of its seat stiffness and sandbag drop height. The seat foundation with a panel-foam support showed the lowest impact force among three seat foundations evaluated. The seat foundation with a foam-spring support subjected to significantly higher impact forces than the one with a panel support if the drop height was less than 13 mm, but as the dropping height increased to 30 mm the significance became less. The impact force on the seat foundation with a panel support became significantly higher than the one with a foam-spring support as the drop height increased to 50 mm.

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