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Corresponding Author:
Dr. David J Hughes. CEng, MIMM, FHEA
Teesside University, School of Science and Engineering, Middlesbrough, UK, TS13BA.
Email: d.j.hughes@tees.ac.uk

COMPARISON OF IMPACT ENERGY ABSORBANCE BY VARIOUS COMBINATIONS OF HIP PROTECTOR AND FLOORING MATERIAL

Authors
Dr. David J Hughes[1], Prof. Farhad Nabhani[1]
[1] Teesside University, School of Science and Engineering, Middlesbrough, UK, TS13BA.

Abstract

Understanding the nature of blunt force trauma and the energies involved is key to their effective attenuation. This study compares and analyses the energy absorbance of various combinations of hip protectors and flooring materials to identify fracture prevention design variables. Testing is performed using a dynamic impact rig instrumented with linear encoders and a piezoelectric impact load cell. This allows for high rate force and displacement measurement to be achieved during impact. Results show the effects of deceleration rate on peak load and measurably define the impact patterns for a range of protective materials with compliant flooring and hip protectors reducing impact forces below the suggested fracture threshold (3742N). We show that the force reduction provided by a hip protector depends on the type of flooring, and is greatest for falls onto carpet with a foam underlay. A combination of soft shell protector with carpet and underlay showed the highest force attenuation (68%). The study shows that the effective selection and implementation of hip protectors in homes and care facilities must include the consideration of flooring type. The identification of peak deceleration rates will also inform the future development of multi-material protective aids.

Keywords:
Blunt Force Trauma, Hip, Impact, Fracture

Introduction

Hip fractures have significant implications for the elderly, increasing mortality by 10-20% in women within a year and leaving one third of sufferers with a major decline in independence in activities of daily living [1]. It is estimated that 4.5 million people worldwide will suffer a hip fracture each year by 2050 [2]. Significant work has aimed to reduce the energy transferred into the hip causing fracture using hip protectors and compliant flooring [3-7]. A recent review of compliant flooring has demonstrated its potential for preventing fall-related injuries [8]. Hip protectors have been have also been assessed for preventing fractures, particularly in nursing home residents [9]. Foams and rubbers are used in both soft shell hip protectors and compliant flooring to absorb impact energy while hard shell protectors are used to deflect the force from directly transferring into the bone. Current testing methods for hip protectors measure peak compressive force transferred to the proximal femur using a single axis load cell applied to a joint model [10,11,12]. While compressive force measured in the bone gives an accurate reflection of transferred force during impact it does not provide detailed information on the energy absorbance characteristics of fall attenuating devices. This study employs linear encoders alongside the current rig to more accurately understand the impact cushioning, energy absorbance and peak velocity damping of a variety of impact attenuating designs. Linear encoders allow for high accuracy and rate position, speed and velocity measurement during impact testing.

It is well established that fracture likelihood is a combination of peak loading and peak velocity [6, 12-15]. Improved knowledge is required to define how effectively hip impact attenuating devices absorb energy and reduce peak impact velocity. Greater understanding is specifically required to understand the relationship between floor type and different hip protector effectiveness. This information will inform the selection and implementation of protective aids and advise the design of future protective devices. Accordingly, this study will review a selection of hip impact attenuating device combinations during simulated impacts to define energy absorbance characteristics and the interworking of hip protectors and flooring types.

Materials and Method

Impact conditions.

Three standard hip protector types and two flooring types are assessed to compare a range of common fall conditions. The rigid control condition was the surrogate hip model with 5mm-thick silicone elastomer synthetic skin directly loaded onto a fixed steel plate. Synthetic skin is used to reflect the top surface soft tissue response and frictional response to the attenuators [16,17]. The following conditions are designed to attenuate impact forces from this ridged control datum. The three hip protectors assessed represent standard hip protector designs; a soft shell protector, a hard shell protector and a rate-sensitive, non-Newtonian foam protector.

The soft shell is a 15mm thick closed-cell EVA-polyethylene foam (soft hip Fallsafe). The hard protector has a hard nylon shell with interior elastomeric foam rim (HIPS). The rate-sensitive non-Newtonian foam protector is a 15mm D30 elastomer (Fallsafe). The two flooring types assessed represent common fall conditions being based on common carpet with underlay (C&U) (7mm polyester cut pile carpet with 9.5mm rubber sponge underlay (Duralay Majestic BS5808)) and 10mm Poron compliant flooring (Poron performance Urethane compression foam. 10mm. (Rogers corp. Woodstock. USA)). The 10mm Poron compliant flooring is uniform density foam with a Shore "A" hardness of 13, a 2mm vinyl top layer (Shore "D" 30) is applied to simulate in-use conditions.

Impact simulation

The Teesside University hip impact simulator (Fig 1.) used is this investigation is closely based upon Robinovitch et.al. [10] to allow for comparison to existing datasets but with developments made to the rig instrumentation. The system is based around a drop tower with surrogate hip model placed at the base (Fig.1.). The standard drop mass of 28Kg and 47kN/m stiffness spring representing pelvic stiffness are used [10].

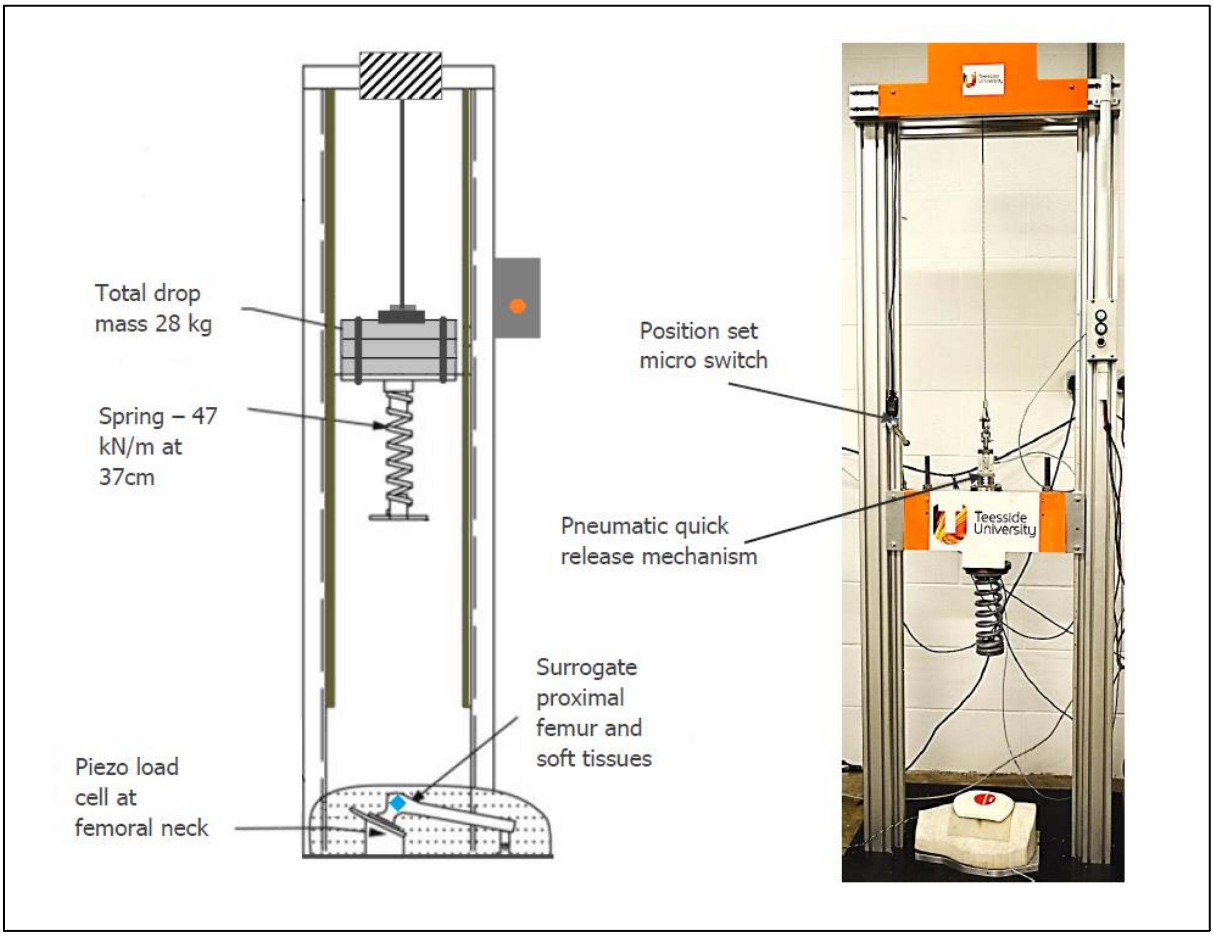

Figure 1 - Hip impact rig

The rig is instrumented with a piezo-electric load cell (Dytran 1051-V. *DYTRAN INSTRUMENTS INCORPORATED, Chatsworth, USA*) placed at the femoral neck. Piezo-electric load cells allow for high resolution measurement of dynamic impact forces displaying greater responsiveness and ruggedness than strain gauge sensors due to their higher stiffness [18]. Two linear encoders (Renishaw rgh41t50d05a 10µm RGH41 series) are mounted to the drop guide rails. Two encoders are used to cancel out any effect of an unbalanced fall or rebound, results displayed in the current paper are based on the average between the two sensors. As can be seen from the position/time trace (Fig 2.) the encoders track the drop head energy deflecting below zero following impact. All data is collected using Micro-measurement 8000-8-sm data collector at 10kHz. Tests are repeated ten times for each protective combination.

Results and Discussion

Energy absorbance

The energy dissipation of the protective medium is represented by the coefficient of restitution (*e*) which is the amount of kinetic energy that remains following impact. It is the ratio between the velocity at impact and the velocity at separation as the drop mass rebounds. The ridged control (BASE) shows a 79% energy conservation indicating minimal damping from the surrogate hip model, soft tissues and pelvic displacement. These values can be correlated closely with the rebound heights shown in Fig 2.

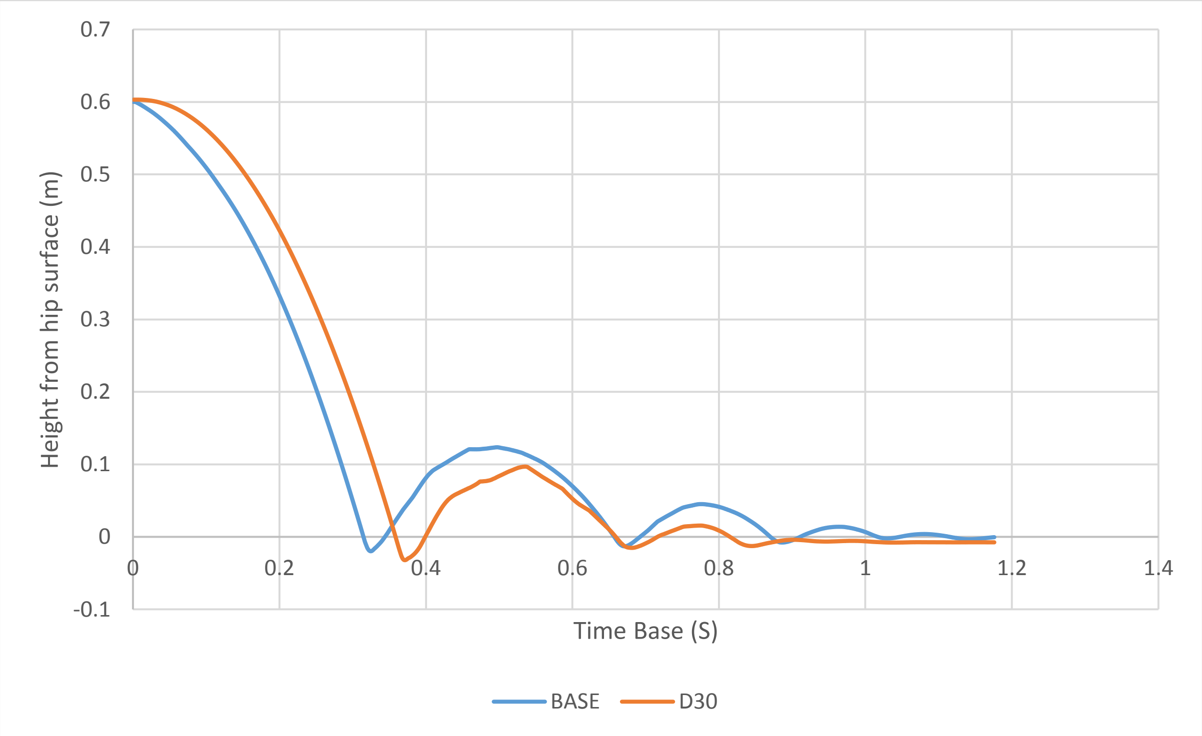

Figure 2 - Drop Profile - Unprotected hip vs. D30 Protector.

Deceleration rate

Deceleration rate is the rate at which the drop mass slows down before rebounding. A lower deceleration rate indicates greater impact cushioning by the impact surface. Rate of deceleration is calculated by the measured impact velocity squared divided by twice the deceleration distance. The G-force value is equally a vector deceleration of the drop mass. A reduction in impact acceleration translates to a reduction in impact force due to the relationship *f=ma (where a could be replaced by -G)*.

The ridged control condition shows a deceleration rate of 301.7m/s^2 (30.8G). Floor type has a significant effect in reducing impact acceleration, maximum reduction is seen in the 10mm Poron compliant flooring (-137m/s^2) which translates to an average 4610N (54%) reduction. The 10mm Poron flooring offers significant reduction in peak G, though the addition of hip protectors does not significantly further reduce measured G (Fig3). The softer and less elastomeric C&U shows lower initial damping but when combined with a hip protector provides improved protection. 10mm Poron compliant flooring is more elastomeric, absorbing more energy from the initial impact and transferring an already significantly reduced load and rate into the hip protector. This significantly reduces the effectiveness of the hip protectors limiting the D30 to a 6.8% average improvement in energy absorbance compared with 10mm Poron flooring alone. The greatest reduction in G is seen with the soft hip protector paired with C&U (10G peak impact). This response is seen due to the increased deceleration time as the softer materials elastically deform. Further work can now be performed to model and optimise the mechanical properties of soft elastomeric foams for maximum impact cushioning under these load conditions.

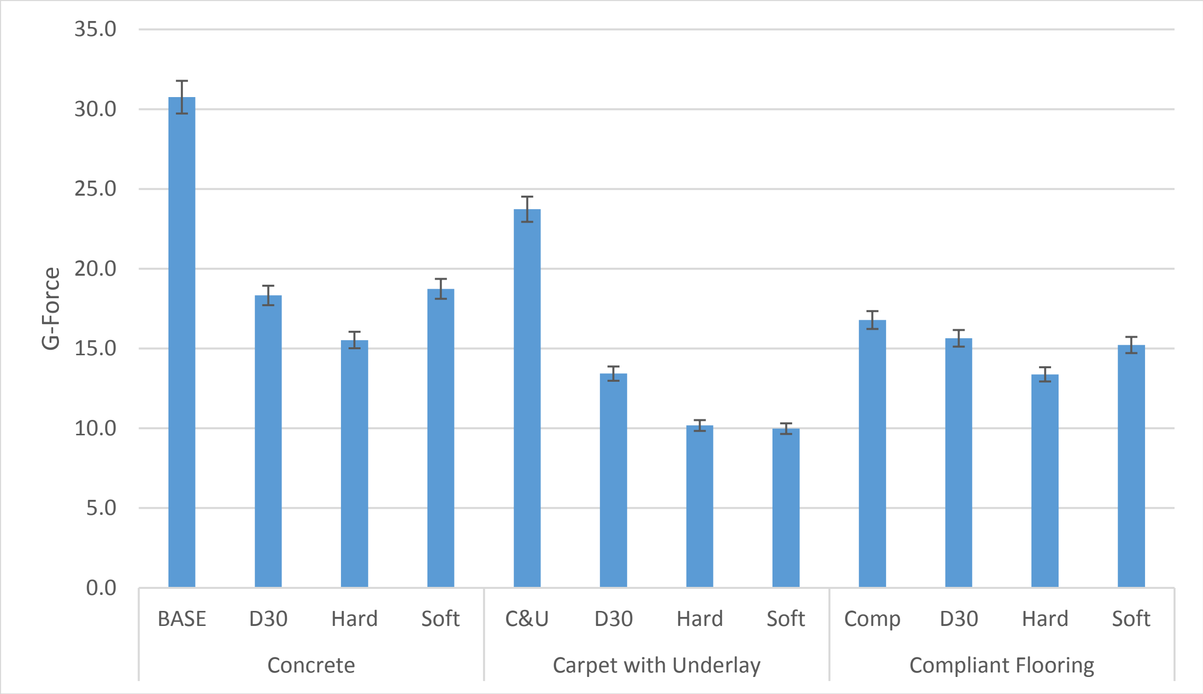

Figure 3 – Average G-Forces at point of impact (error bars show mean deviation).

Reducing the G-Force is a key factor in fracture reduction as it is the combination of peak load and peak acceleration at impact that contributes to resultant stress transferred into the Femoral neck [6,13,14].

The complex and dynamic nature of a standing fall includes pelvic stiffness and body contortion. It can be seen from figures 4 and 6 that the deceleration rate is not constant, this is due to the multi-component damping system present. Using the described method these changes in rate can be measured and analysed, thus identifying impact patterns during the impact phase of a fall.

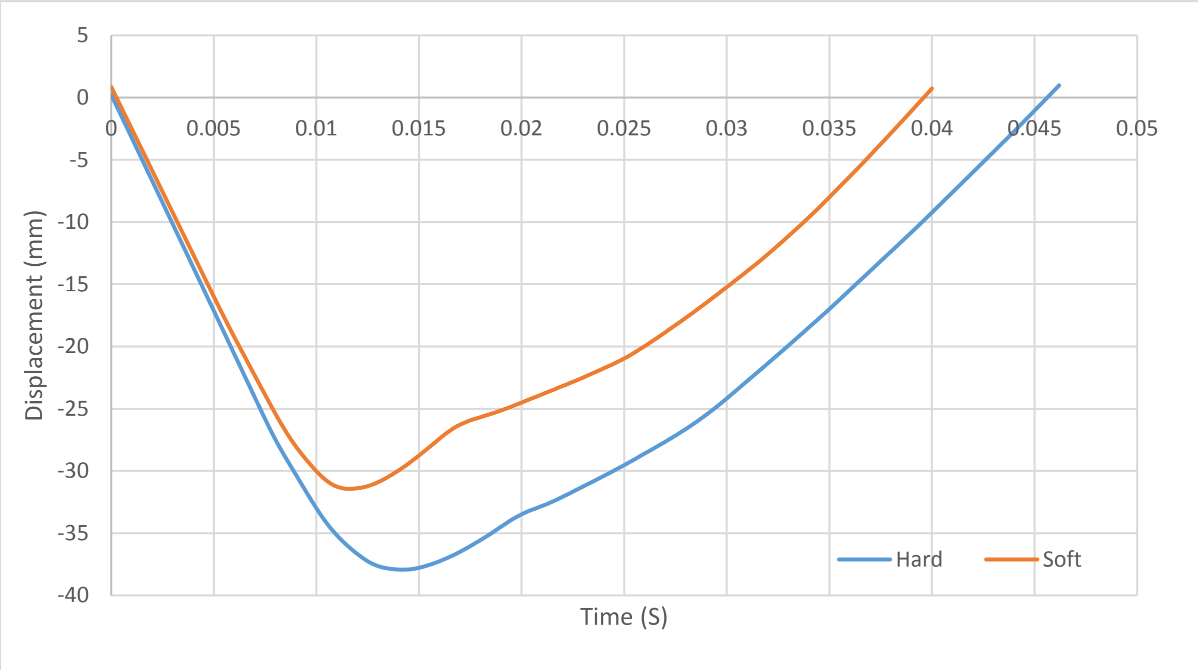

Figure 4 – Experimental displacement-time graph results for Soft Shell Protector and Hard Shel Protector. Significant shifts in spring rate can be seen across the impact profile caused by the multi-material damped system.

Table 1 – Comparison of results for each testing condition.

		y_c (m)	e	a (m/s²)	G	F_E (N)	F_E Std. Dev.	F_{Ic} (N)	F_{Ic} Std. Dev.
Concrete	BASE	0.0199	0.405	301.7	30.8	8447.1	165.4	8294.3	223.5
	D30	0.0322	0.560	179.8	18.3	5033.9	91.5	5126.2	96.2
	Hard	0.0379	0.476	152.4	15.5	4266.8	73.7	4345.1	92.0
	Soft	0.0314	0.480	183.8	18.7	5147.6	96.9	5242.0	104.3
Carpet with Underlay	C&U	0.0248	0.432	232.8	23.7	6517.9	106.2	6637.5	174.8
	D30	0.0439	0.503	131.7	13.4	3688.2	63.9	3755.9	74.7
	Hard	0.0590	0.574	99.8	10.2	2795.2	48.6	2791.5	52.4
	Soft	0.0590	0.535	97.9	10.0	2741.2	47.5	2791.5	52.4
Compression Flooring	Comp	0.0351	0.439	164.7	16.8	4610.8	77.4	4695.4	83.5
	D30	0.0377	0.471	153.4	15.6	4296.3	78.1	4375.0	86.6
	Hard	0.0440	0.489	131.3	13.4	3675.7	69.2	3743.1	68.8
	Soft	0.0387	0.500	149.3	15.2	4180.8	70.1	4257.5	78.6

Note.

y_c	m	Deceleration distance
e		Coefficient of Restitution
a	m/s^2	Rate of deceleration
G		G-Force
F_E	N	Force – linear encoder
F_{lc}	N	Force – load cell

Peak Impact force

Impact force is calculated from the linear encoder (F_E) based on the mass and measured deceleration rate, this is compared with the load measured in the piezo-electric load cell (F_{lc}). The ridged control condition (BASE) shows low variation between peak loadings measurements; 8447.1N F_E and 8294.3N F_{lc} ($s^2=25.5$) (Table 1). All test conditions show reduction in peak loading transferred to the femoral neck. There is a clear and direct correlation between the measured impact load and the declaration rate (Fig5). Measured results can be compared to the average hip fracture threshold of elderly people 3472N (Range 2110 to 4345N) [10]. This indicates that, in the present study, only two test conditions exceed the average hip fracture threshold of elderly people. Previous studies have shown more favourable results but at lower accelerations and masses than those recommended by the International Hip Protector Research Group used in this study [6,19].

A notable finding from this study is the effect carpet has on improving the cushioning effects of hip protectors. This is due to the increased deceleration distance recorded during impact (see table 1), which produces a more gradual, rather than instantaneous, change in velocity. Energy absorbance is directly related to the recovery of materials during and after impact. Due to the nature of the carpet, and particularly underlay tested, it exhibits slower recovery properties than other flooring types. The combination of slow and quick recovery materials produces a blending of effects, generating a balance of energy absorption and impact cushioning. The combination of both hard and soft hip protectors with carpet and underlay demonstrate this combination behaviour exhibiting both improved cushioning and energy absorption. The D30 protector displays some of this combined benefit however its effectiveness is limited by the less dense materials damping effect reducing impact velocity. D30 is a rate sensitive material and so its optimum properties are achieved at high velocities.

Unlike the application of carpet, Poron appears to limit the effect of hip protectors. Where two energy absorbing materials are combined with similar stiffness properties but different damping capabilities the one with higher damping will be slower to recover from impact, and will absorb and dissipate more energy during impact. The 10mm Poron demonstrates high damping characteristics and therefore becomes a limiting factor for the effectiveness of other protective mechanisms applied as it absorbs more energy during impact.

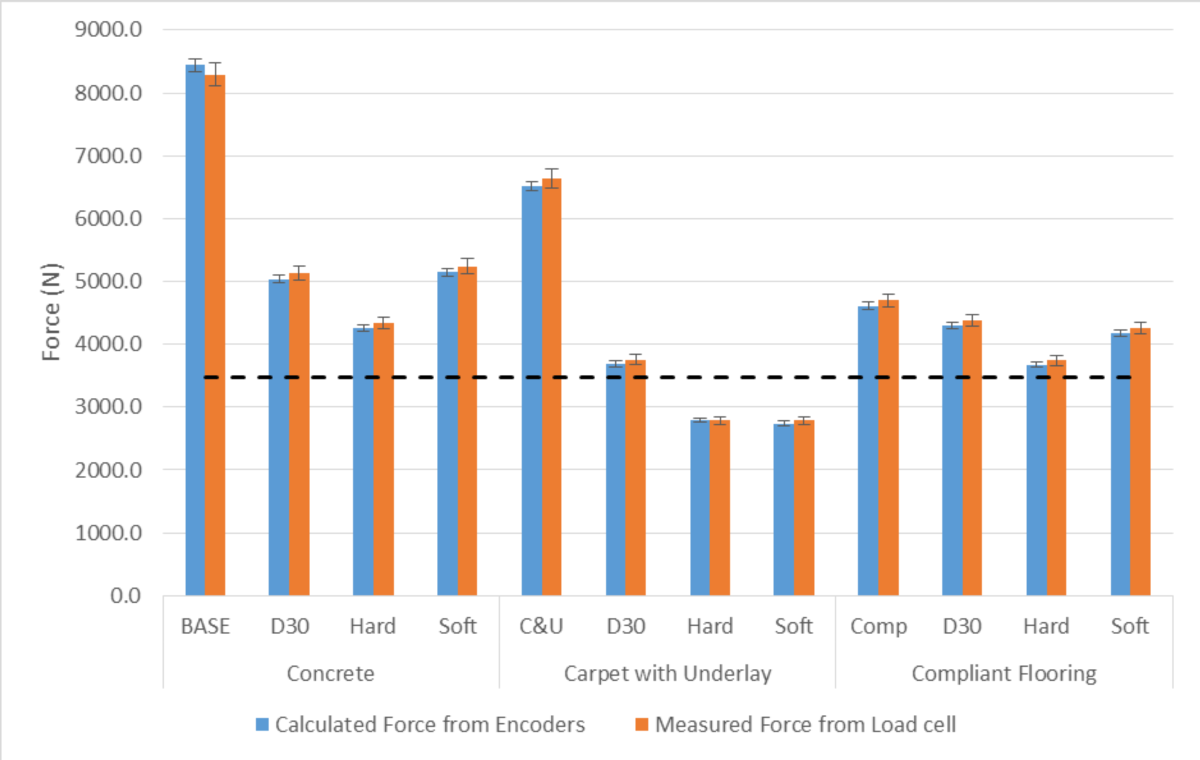

Figure 5 – Forces calculated from linear encoders compared with direct load cell data. All results not significantly different ($p>0.05$). Threshold line equal to average hip fracture threshold of elderly people.

Collected results (shown in Fig5) are similar to those previously published by Ning [19] and Minns [8]. Ning et.al. [19] show similar results when comparing Tatami matting with worn protectors that this study shows with 10mm Poron flooring. These mats provide similar improved elastic response and damping which limits the effectiveness of worn protectors.

Conclusions

The characterisation of impact loads transferred to the hip complex has been demonstrated using dynamic measurement techniques. The application of displacement measuring linear encoders provides live trace mapping of impacts leading to a greater understanding of multi-material impact characteristics resulting from falls. These traces show that where foam density, in flooring or hip protector, is reduced initial impact peak stress is reduced and impact cushioning improved, this is due to the easier displacement of the less dense material. The carpet with underlay is the least dense material in the current study and leads to the most significant combined reductions. It has been shown by this series of experiments that though compliant flooring and hip protectors can help reduce impact loads only a combination of techniques is adequate to lower forces below the suggested fracture threshold (3742N). A combination of soft shell protector with carpet and underlay showed the highest force attenuation (68%). The effectiveness of the D30 hip protector is limited by softer flooring as its peak performance, being rate-sensitive, is achieved at high velocity which is reduced by the less dense materials damping effect illustrated in figure 6. A limitation of the current study is the number of protector pads and flooring materials compared. Further work should look to translate the method to a wider range of protective media and consider differences in fall rate and mass.

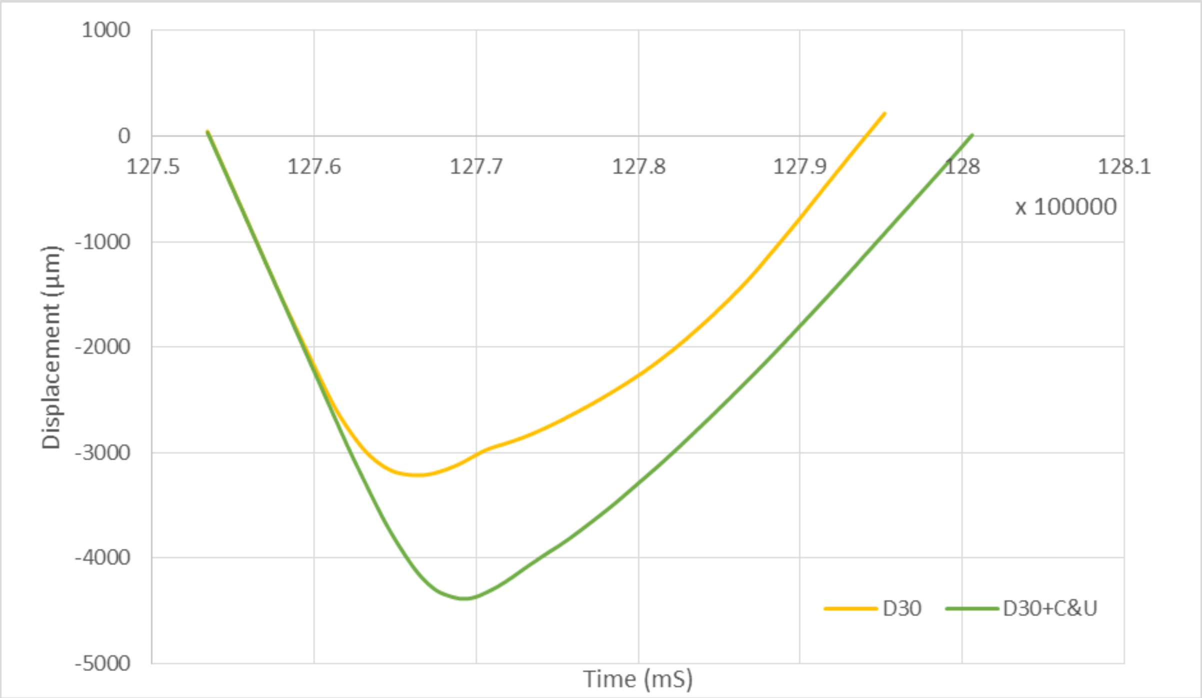

Figure 6 - Experimental displacement-time graph results for D30, D30+C&U. a.D30 protector damping period 8834mS. b. D30+C&U damping period 12247mS.

Peak deceleration rates can be used to design future hip protectors and compliant flooring, specifically looking to design multi-stage protectors which account for the variability in loads and rates. These protectors may include gradient-density foams and dynamically active dampers. Clearly if protective hip pads are to be used the effect of flooring density must be considered for them to be effective.

Conflict of interest statement.

All authors have no financial or personal conflicts of interest to report.

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