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The effects of pad geometry and material properties on the biomechanical effectiveness of 26 commercially available hip protectors

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ABSTRACT

Wearable hip protectors (padded garments) represent a promising strategy to decrease impact force and hip fracture risk during falls, and a wide range of products are currently marketed. However, little is known about how design features of hip protectors influence biomechanical effectiveness. We used a mechanical test system (simulating sideways falls) to measure the attenuation in femoral neck force provided by 26 commercially available hip protectors at three impact velocities (2, 3, and 4 m/s). We also used a materials testing machine to characterize the force–deflection properties of each device. Regression analyses were performed to determine which geometric (e.g., height, width, thickness, volume) and force–deflection properties were associated with force attenuation. At an impact velocity of 3 m/s, the force attenuation provided by the various hip protectors ranged between 2.5% and 40%. Hip protectors with lower stiffness (measured at 500 N) provided greater force attenuation at all velocities. Protectors that absorbed more energy demonstrated greater force attenuation at the higher impact velocities (3 and 4 m/s conditions), while protectors that did not directly contact (but instead bridged) the skin overlying the greater trochanter attenuated more force at velocities of 2 and 3 m/s. At these lower velocities, the force attenuation provided by protectors that contacted the skin overlying the greater trochanter increased with increasing pad width, thickness, and energy dissipation. By providing a comparison of the protective value of a large range of existing hip protectors, these results can help to guide consumers and researchers in selecting hip protectors, and in interpreting the results of previous clinical trials. Furthermore, by determining geometric and material parameters that influence biomechanical performance, our results should assist manufacturers in designing devices that offer improved performance and clinical effectiveness.

1. Introduction

Hip fractures (i.e., fractures of the proximal femur) are a major public health problem for older adults. The lifetime risk for hip fracture in the USA is 17% for Caucasian women and 6% for Caucasian men (Cummings and Melton, 2002). While bone density is a major determinant of fracture risk, the majority of hip fractures occur in persons who do not suffer from osteoporosis (Dargent-Molina et al., 1996; Taylor et al., 2004). Instead, fall mechanics and the resulting loads applied to the proximal femur during impact are the factors most closely associated with the risk of suffering a hip fracture (Cummings and Nevitt, 1994). Sideways falls increase hip fracture risk by 5-fold when compared to forwards or backwards falls (Hayes et al., 1993); the risk increases by 32-fold when direct impact to the greater trochanter occurs (Nevitt and Cummings, 1993). Accordingly, protective devices that reduce the force applied to the proximal femur during fall-related impacts have the potential to reduce hip fracture risk.

Wearable hip protectors (padded garments) are a promising strategy for decreasing hip fracture risk by reducing the loads applied to the proximal femur during fall-related impacts. Until recently there were no established guidelines for assessing the biomechanical and clinical effectiveness of these devices (Cameron et al., 2010; Robinovitch et al., 2009). Consequently, there are currently more than two dozen commercially marketed

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hip protectors in North America that utilize a surprisingly diverse array of design philosophies, materials, and geometry. The first generation of hip protectors used 'hard shell' domes, which bridged over the greater trochanter, to shunt energy away from the proximal femur during impact (Kannus et al., 2000; Lauritzen et al., 1993). More recently, soft shell hip protectors have become more common. These products reduce the force applied to the proximal femur by absorbing energy in the pad material, and reducing the local stiffness over the greater trochanter through a "springs-in-series" mechanism (Laing and Robinovitch, 2008a, 2008b).

Researchers have shown that the biomechanical effectiveness (i.e. force attenuation capacity) of hip protectors is influenced by external factors including impact velocity, soft tissue properties, and pelvic surface geometry (Kannus et al., 1999; Laing and Robinovitch, 2008b; Mills, 1996; van Schoor et al., 2006). Presumably, pad geometry (thickness, surface area) and material properties (stiffness, damping) also affect force attenuation. In controlled experiments, Robinovitch et al. (1995) found that increasing the thickness of 'horse-shoe' shaped pads (of identical surface area) from 18 to 38 mm increased force attenuation by 66%. However, the force–deflection and geometric properties of commercially marketed hip protectors vary widely, and it is not known whether specific biomechanical variables govern (or explain) between-product variations in force attenuation. Such information should guide users in the selection of products, and manufacturers in the design of a new generation of hip protectors with increased biomechanical effectiveness.

The goals of this study were therefore to test the hypotheses that the force attenuation provided by a range of hip protectors when positioned correctly over the greater trochanter would significantly associate with their geometry (e.g. width, thickness) and force–deflection properties (e.g. stiffness, energy absorption). Towards these ends, we used a mechanical test system to measure the force attenuation provided by 26 commercially available hip protectors. For each hip protector, we also used a materials testing system to measure the force–deflection properties, and digital calipers to measure pad geometry. Regression analyses were used to test whether force attenuation depended on material and geometric properties.

2. Methods

2.1. Hip protector brands and characteristics

We used a combination of literature review and Internet searching (using search terms such as "hip protector", "hip pad", "seniors", and "hip fracture") to identify 26 commercially available hip protectors from distributors in nine different countries for testing (Table 1; Fig. 1). We used a binary variable ($material_{type}$) to categorize the products according to their dominant material type (hard versus soft shell). Specifically, 'soft shell' protectors consisted primarily of foam and fabric (21 models), while 'hard shell' protectors contained a relatively stiff material that bridged over the greater trochanter (5 models). We also categorized the protectors based on their dominant geometry type ($geometry_{type}$), which describes the nature of the interface between the hip protector surface and the skin overlying the lateral pelvis. In particular, we categorized 21 models as 'touching', and 5 models as 'not touching' the skin directly overlying the greater trochanter. Basic information on the material types used in the each protector is available as Appendix A in supplementary website material.

2.2. Impact force attenuation tests

We used the Simon Fraser University hip impact simulator (Fig. 2) to measure the biomechanical effectiveness of each hip protector. The system and test method have been described in detail previously (Laing and Robinovitch, 2008b, 2009), and are generally compatible with guidelines from an international team of biomechanics and clinical experts (Robinovitch et al., 2009). The system consists of an impact pendulum and surrogate pelvis released from an inclined position by an electromagnet to strike the ground in a horizontal position. The surrogate pelvis is comprised of foam-rubber soft tissues and an instrumented proximal femur (Sawbones, Vashon, WA, USA). Surface geometry and local variation in soft tissue stiffness match average measurements from older women to within one standard deviation (Laing and Robinovitch, 2008b). The surrogate pelvis is connected to the pendulum via leaf springs that simulate the compliance of the

Table 1
Manufacturer, general design approach, and geometric variables measured from 26 hip protectors.

Hip protector name	Company	$Material_{type}$	$Geometry_{type}$[a]	Height (mm)	Width (mm)	$Thick_{pad}$ (mm)	$Thick_{wearing}$ (mm)	Volume (mm^3)
Alimed® Hip Shield	AliMed®	Soft	Y	170	190	14	14	452,200
Anatech	Anatech	Soft	Y	160	210	13.5	14	453,600
Bort	Bort Medical	Soft	Y	170	150	15	19	382,500
Caresse	Remploy Healthcare	Hard	Y	230	140	22	22	708,400
ComfiHips™	ComfiHips LLC	Soft	Y	195	145	17.5	17	494,813
FallGard	FallGard	Soft	Y	175	120	17.5	19	367,500
Hip Guard	HipGuard™ Ltd.	Hard	N	155	165	20.4	19	521,730
Hip Shield	Promedics	Soft	Y	200	150	16	17	480,000
HipEase	Patterson Medical/Sammons Preston	Soft	Y	170	150	32	31	816,000
HIPS	Qvortrup Medical A/S	Hard	N	160	110	5	25	88,000
Hipsaver®	Hipsaver®	Soft	Y	220	200	18	19	792,000
Hornsby Comfy Hip	Hornsby Comfy Hips Pty Ltd	Soft	Y	195	165	18	21	579,150
Impactwear® - Flexible	Impactwear	Soft	Y	155	120	16	19	297,600
KPH®	Medlogics	Hard	N	190	95	15	31	270,750
LYDS	Comfortable	Soft	Y	205	135	6.5	7	179,888
Pelican Super Soft	Pelican Manufacturing PTY LTD	Soft	Y	170	160	21	22	571,200
Pelican Washable	Pelican Manufacturing PTY LTD	Soft	Y	160	150	17	18	408,000
Pelican 179P	Pelican Manufacturing PTY LTD	Soft	Y	155	140	23	24	499,100
Posey Heavy Duty	J.T. Posey company	Soft	Y	170	140	14.5	14	345,100
Posey Regular	J.T. Posey company	Soft	Y	165	140	13	13	300,300
ProtectaHip+Plus®	Plum Enterprises INC	Soft	Y	180	180	18	20	583,200
ProtectaHip®	Plum Enterprises INC	Soft	Y	180	180	14.5	16	469,800
Safehip® Air-X™	TYTEX A/S	Soft	N	210	185	16	16	621,600
Safehip® Classic	TYTEX A/S	Hard	N	160	115	8.6	24	158,240
Secure	Personal Safety Corporation	Soft	Y	165	145	16	16	382,800
WonderHip™	Vital Base AS	Soft	Y	193	137	15	16	396,615

[a] $Geometry_{type}$ indicates whether the protector touches (Y) or does not touch (N) the skin directly overlying the greater trochanter.