



Test systems for the biomechanical evaluation of hip protectors: a systematic review

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Abstract

Various mechanical and biomechanical test systems to evaluate the effectiveness of hip protectors designed to prevent hip fracture as a result of falls were examined in this review. The articles considered were selected systematically. The effect of differences in design criteria was demonstrated, and it was observed that the impact energy employed during testing dramatically affects the performance of the hip protector. Over the past three decades, researchers have continuously experimented with various systems to determine the efficacy of various hip protectors. The primary aim has been to make informed decisions in optimizing hip protector design. This article provides a systematic review of various test systems employed in the determination of the biomechanical efficacy of hip protectors. A systematic literature search was carried out, and 28 relevant articles were included to demonstrate the effect of test systems in the evaluation of the biomechanical effectiveness of hip protectors. Methodological studies illustrated the appropriate use of impact testing systems for the simulation of hip anatomy and fall dynamics in evaluating the effectiveness of hip protectors in preventing a hip fracture. This systematic review has demonstrated the effect of the variability of test systems on the evaluation of impact attenuation by various hip protectors. The lack of standardized test systems accounts for the inconsistencies in the test results of the efficacy of hip protectors. This has been a major challenge in the efforts of researchers to optimize the interventions. The standardization of test systems may require needed improvements immediately as opposed to the development of new interventions in order to ensure that only hip protectors with adequately proven efficacies are deployed for clinical trials or for the protection of the hips of vulnerable individuals from sideways impact.

Keywords Biomechanical effectiveness · Fracture · Hip protector · Hip pad · Mechanical testing · Osteoporotic hip

Introduction

A hip protector is a specialized pad designed to prevent fall-related hip fracture among frail elderly individuals [1, 2]. Hip fractures cause significant morbidity and are associated with increased mortality, loss of independence, and financial burden [3–5]. A global annual number of 6.26 million hip fractures is projected to have a clinical and economic implication on the aged population by the year 2050 [6–9]. Treating hip fracture is very expensive, costing a typical patient approximately \$40,000 in direct medical cost in the first year

following a hip fracture and approximately \$5000 in the years that follow [10]. Therefore, the mechanism of hip fracture and the choice of prevention strategy are of great interest [2].

Hip fractures may be prevented by utilizing three main strategies. The first strategy is to avoid falls by increasing coordinative responses and balancing power [11, 12]. The second strategy is to improve bone quality with the use of medication. However, bone strengthening results may take years to be effective [13]. The third strategy is to effectively attenuate the impact force to below the fracture threshold [11, 14–17]. This third strategy provides an immediate effect and could help curtail the menace of hip fracture.

Hip protectors have been proven to be an effective strategy in reducing the impact force to the hip in a sideways fall [18]. Principally, there are two distinctive types of hip protectors, namely “energy shunting type” or “energy-absorbing type” [19], generally called the hard shell and soft shell hip protector, respectively. The impact force in a fall is distributed into the surrounding soft tissue by the energy shunting type of hip

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protector, while the energy-absorbing type is usually made of compressible material and diminishes the force of impact [20]. Both of these interventions intend to reduce the impact force at the hip beneath an estimated fracture threshold [1, 21]. Other designs have blended the energy shunting and energy absorbing materials, such as by incorporating a thin preformed shell within a softer layered material [22] or through the use of composite materials [20, 23].

Some clinical trials, cluster randomized and nonrandomized trials with fewer biases, have made conflicting arguments on the ability of the hip protectors to attenuate impact forces [2, 24]. Kiel et al. [24], using a finely designed, multicenter, randomized control clinical trial, reported the failure of hip protectors to demonstrate a protective effect on hip fracture incidence in nursing home residents despite high adherence, whereas a 50% reduction in hip fracture was credited to the use of a hip protector in a cluster randomized trial [2]. Meta-analyses have also been divided along this line. Sawka et al. [25] reported a decreased risk of hip fractures in elderly nursing home residents using the Bayesian random effects model for pooling binary outcome data from randomized cluster trials (CRTs) with individually randomized trials (IRTs), while Parker et al. [26] reported that the effect of hip protector use for preventing fractures among nursing home residents was minimal, while it was not effective among community-dwelling elderly individuals. Although studies have improved the design of clinical trials and addressed methodological biases, employing a biomechanically effective hip protector that has undergone thorough testing may sway the argument in favor of the hip protector, as a recent finding in a Cochrane review demonstrates [27].

Additionally, there is a lack of conformity in the design and deployment of hip protectors, responsible for numerous variations in the design, properties, and performance of several commercially available hip protectors [28]; therefore, effective test systems need to be developed to assess the biomechanical efficacy of hip protectors to identify those with potential efficacy in clinical trials [19].

In this systematic review, methodological aspects of investigating the effectiveness of hip protectors are presented, and characteristics of test systems used by various researchers in the evaluation of the mechanical and biomechanical effectiveness of hip protectors are examined.

Objectives

- Access laboratory studies that quantify the appropriate force attenuation properties of hip protectors
- Identify various methods and improvements in the mechanical and biomechanical analyses of the effectiveness of a hip protector

- Test the null hypothesis that the percentage force attenuation is not influenced by the impact energy used in testing

Methods

Searches on “Effectiveness of hip protectors” in Science Direct, PubMed, and the JAMA Network databases were carried out with the specific keywords “mechanical test” and/or “biomechanical test.” Before the keywords were applied, Science Direct gave a total of 668 results, and PubMed provided 35 results. The result was drastically reduced to 15 for Science Direct when the keywords were applied, 13 of which met the criteria for inclusion in this review. Twelve research articles and one book chapter were accepted. The JAMA Network gave no results after the application of the keywords, while PubMed gave 15 articles, of which five were also removed for not meeting the criteria or for repetitiveness. A reference link was also searched, and five additional pieces of research were included in the analysis.

Exclusion criteria

All studies on randomized or quasi-randomized controlled trials (RCTs) on the use of hip protectors without a mechanical test or biomechanical test of the hip protector were excluded.

Expected outcome

- Impact energy
- Peak impact force
- Percentage force attenuation

Results

A total of 28 articles that met all the inclusion criteria were used to evaluate the impact of test systems on the results of mechanical and biomechanical analyses of hip protectors (Fig. 1). Apart from discussing the impact of test systems on the analysis of hip protectors, this article also presents a brief overview of the typical process used to analyze a hip protector.

Methodological aspects of the investigation of the effectiveness of a hip protector

Typically, a test system is composed of a surrogate pelvis that strikes (or is struck by) an impact surface, simulating the impact phase of a fall. The data generated from these test systems are crucial for the design and development of hip protectors and for informing consumer purchase decisions [19, 29–32].

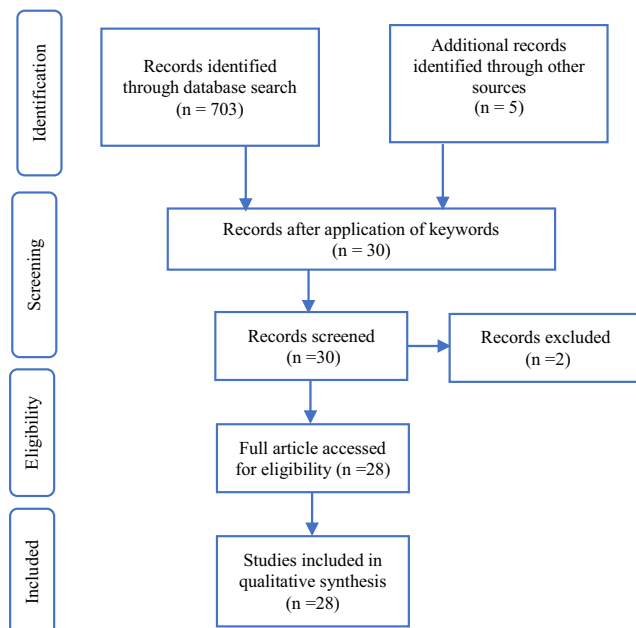


Fig. 1 Flow of studies

A test system for the evaluation of hip protectors is typically complex because it is aimed at measuring the effect of an intervention in the event of a physiological activity that currently does not have a standard outline guiding the characteristics of systems to be incorporated [33]. The test system requires a large number of decisions within the process of developing an appropriate model to evaluate the desired effect. This section gives an overview of this selection process and examples of choices made by researchers in developing the test system, a significant factor that can potentially influence the reporting of the hip protector effectiveness.

1. Modeling the musculoskeletal anatomy

The first characteristic of the test system capable of influencing the result of a hip protectors' effectiveness is the design of the constituent parts of the protected subject area. There are variations in the level of details incorporated in various designs. Deciding the anatomical structures representing the impact site is a significant step in the development procedure. Some researchers modeled the greater trochanter as an axially symmetrical ellipsoid, modeling just the protruding hard tissue as the specific area to be studied [34, 35]. Some have modeled the isolated femur [36], while others have attempted to include the features of the entire pelvis area by incorporating springs [35, 37, 38]. Additionally, some impact site representations do not include the anatomical shape of the femur, but tests were done using mechanical anvils or hip-shaped anvils as the representation of the pelvis [20, 28]. This representation is aimed at having a simple model that does not represent the full surrogate but gives useful assessments [11, 15, 39]. Some of the surrogate femurs reported

include porcine [11], cadaveric hip bone [40], aluminum [41], steel [36, 42], ABS (acrylonitrile butadiene styrene) copolymer [39], and wood [30].

In all, the lower torso mass and the rigidly supported femur are the two primary expressions for the effective mass [43]. The lower torso mass arrangement is usually supported with springs to limit impact [35, 37, 44, 45]. Unlike Choi et al. [45], Laing et al. [44], and Bulat et al. [34], most researchers do not drop the instrumented hips on a fixed floor, perhaps because of convenience. In most test rigs, a large rigid mass known as an impactor is constrained to move with one degree of freedom along one axis and used to strike the perpendicular surface of the greater trochanter of the fixed hip [46]. A good model must, therefore, seek to closely match the peak impact force, the moment of force, the contact area, and the pressure applied to the proximal femur, since the skeletal geometry influences the distribution of impact loads at the skin surface [47]. Correspondingly, an inaccurately chosen effective mass or an inappropriately applied geometry could produce a peak force that is higher than the forces predicted in a sideways fall [30, 35, 48].

2. Modeling of soft tissue

The characteristics of the soft tissues beneath the skin overlying the hip region also have an appreciable effect on the impact force on the proximal femur. The thickness of the soft tissue over the greater trochanter has been demonstrated to affect the consequence of fall, correlating with a decrease in peak force and an increase in energy absorption at the tissue level [31, 49–51]. The soft tissue located over the greater trochanter is said to be the stiffest compared to the posterior region [44, 49]. Therefore, it must be simulated appropriately for biofidelity. Researchers have incorporated physiological simulations of soft tissue thickness and stiffness into systems that evaluate the hip protector's effectiveness [43, 52]. The effect of trochanteric soft tissue thickness (TSTT) on peak force using finite element models was also investigated by Majumder in multiple studies, which concluded that TSTT had a significant effect on hip fracture risk [53, 54].

Although it is generally challenging to model the soft tissue, different materials have been used to simulate the soft tissue thickness and stiffness. Materials such as polyethylene foam [34, 49], oil-extended jelly-like red polymer [39], CF-45 Blue CONFOR foam (Safety Devices Ltd., Great Britain) [42], soft flexible foam with a thickness of 3 cm [23], sponges [15], and silicon elastomers such as Silipos gel (Silipos UK Ltd., Middlesex, UK) [14] have been employed. This variability also affects the impact distribution to the area of the simulated soft tissues in the various rigs. The results of an experiment would, therefore, be a function of the soft tissue thickness and stiffness, among other factors [44].

3. Impact energies

After the models of the proximal femur and the soft tissue have been decided, the test system requires the impact energies to be decided through the determination of the impact velocity. Biofidelity models are hinged around the findings by Feldman et al. [50], which estimates the impact of sideways falls at an average of 3.0 m/s as well as that of Lotz and Hayes [55] measurement of $3.2 \pm 0.5 \text{ ms}^{-1}$. Impact velocity modeling is essential as a measure of the severity of falls and could affect the measurement of the response of both the hip protector and underlying soft tissue, ultimately influencing the estimate of the femoral impact force [53, 56]. In deciding the impact energies to produce fracture-causing impacts, impact mass and the height of fall are the critical factors to determine the impact energy in a fall, thus determining the peak femoral forces [11, 44].

Evaluating the biomechanical efficiency of hip protectors requires not just the simplistic model of the impact mass, geometry, velocity and impact energies but also the thickness and stiffness of soft tissue, impact orientation, nonlinear or linear characteristics of the soft tissue, the type of hip protectors, and its contact and geometry, all of which affect the result of biomechanical efficiency provided by hip protectors. It is challenging to conduct a repeatable experiment, as the effects of these variables are not easily investigated with simple models. However, the effects of impact velocities, which significantly determine the impact energies, have been reported in the literature in the development of standards to evaluate the biomechanical effectiveness of hip protectors [44].

Mechanical testing methods

In the studies included in this review, researchers have characterized the force shunting and energy-absorbing abilities of hip-protecting devices at resisting force during a fall using different test methods, which has led to disparities in the results used in predicting the effectiveness of the hip protectors [33, 43]. This difference in testing methods makes it difficult to deploy only hip protectors that are biomechanically strong and likely to be effective in clinical trials [33]. Most experiments are built on the premise of the documented forces and energies encountered during a fall by laboratory tests on cadavers and from analytical studies [49]. The femur specimen or surrogate is usually subjected to impact forces in the presence or absence of the hip protector, often at defined impact energies (Table 1). Several experimental studies have found sufficient values of attenuated forces and positive impact resistances of various hip protectors, but discrepancies exist in the magnitude of forces obtained [11, 32, 38, 42, 57].

There exist only two test methods with different variations or modifications, namely the drop impact test [14, 28, 36, 39, 42] and the pendulum impact test [48, 58], some of which

have been developed or represented using finite element models [41, 59]. The infinite combinations of effective mass, stiffness, and velocity of the body at impact for a mass-spring model give a researcher the flexibility to produce realistic peak forces for falls from standing height with numerous configurations [60].

Some test systems incorporate physiological values of effective mass, impact velocity, and stiffness to provide a significant estimate of the biomechanical effectiveness of hip protectors while some aim for a mechanical comparison of impact attenuation with a constant value of evaluation in scenarios with and without the presence of a hip protector [61]. Table 1 shows that there is significant unevenness in the characteristics of test systems used by various researchers in the evaluation of the mechanical and biomechanical effectiveness of hip protectors.

To a large extent, apart from the design feature (geometry and materials) of the hip protector itself, the inconsistency in the biomechanical effectiveness of hip protectors observed in the literature can be linked to the variations in the test system configurations employed in testing various hip protectors. Different configurations, as shown in Table 2 have their inherent differences; the selection of material for soft tissue simulation, the magnitude of impact energy, and the type of femur/pelvis/greater trochanter representation all play vital roles [49, 54]. The various rigs used by different researchers can be classified into four broad categories with some modifications in each set (see Table 2). This classification is based on the test rig being either a pendulum or drop tower rig and the configuration of their impact masses. Some prominent modifications found in the literature include the incorporation of springs to simulate the pelvis, exclusion of soft tissue surrogates, and the use of whole femur/specific representations of the greater trochanter or the use of pelvis without any anatomic features.

Parkkari et al. [35], Robinovitch et al. [37], and Kannus et al. [48] incorporated spring fixtures into their pendulum test rigs (pendulum type 1, Table 2) to simulate the stiffness of the hip of an older adult. Similarly, Lam et al. [11] incorporated a similar spring fixture to their drop impact tower (drop tower type 1, Table 2) to represent the human pelvis. In contrast, Mills [39], Nabhani and Bamford [38], van Schoor et al. [42], Wiener et al. [30], Derler et al. [62], Sze et al. [57], Minns et al. [32], Zhang et al. [63], Holzer et al. [28], Okuizumi et al. [40], Lee et al. [23], and Haris et al. [20] produced representative impact velocities and peak forces with a simple drop tower rig without simulating the stiffness of the pelvis with springs, relying more on the physiological geometry and mechanical properties of their femur and explicitly modeled soft tissue.

Laing and Robinovitch [44] and Choi et al. [64] used the Simon Fraser University (SFU) hip impact simulator (pendulum type 2, Table 2), and Li [15] constructed a similar test system without incorporating springs to avoid creating a

Table 1 Characteristic of test systems

Article	Type of rig	Impact energy (J)	Impact velocity (m/s)	Effective mass (kg)	Material of soft tissue	Thickness of soft tissue (mm)	Stiffness of soft tissue on GT (kN/m)	Effective stiffness of pelvis (kN/m)	Peak impact force (unpadded) (N)
Parkkari et al. [35]	Pendulum	50,176	1.6, 3	39	Not incorporated	Not incorporated	Not incorporated	75	8200
Robinovitch et al. [37]	Pendulum	120	2.6	35	Polyethylene foam	18–36	8.5–35	24–78	5810
Parkkari et al. [73]	Pendulum	78	2.0	39	Polyethylene foam	25	Not defined	75	5590
Mills [39]	Pendulum	132	2.6	39	Polyethylene foam	25	Not defined	75	10,400
	Drop impact	8–66	1.1–3.3	12.3	Oil-extended jelly-like red polymer	10	70	Not incorporated	3910
Okuzumi et al. [40]	Drop impact	20.6	2.2	8.4	Not incorporated	Not incorporated	Not incorporated	Not incorporated	3117
Kannus et al. [48]	Pendulum	41	1.4	52	Polyethylene foam	20	Not defined	18.8	3740
	Pendulum	74	1.9		Polyethylene foam	20	Not defined	18.8	6130
	Pendulum	110	2.3		Polyethylene foam	20	Not defined	18.8	9190
Nabhani and Bamford [38]	Drop impact	120	3.12	28	Silicon elastomer (Silastic™)	3	Not defined	Not incorporated	4300
Lam et al. [11]	Drop impact	24	1.98	12	Silicon rubber	6	Not defined	75	4400
Wiener et al. [30]	Drop impact	52.9	3.43	9	Polyethylene foam	5	Not defined	Not incorporated	13,372
	Drop impact	82	4.24	9	Polyethylene foam	5	Not defined	Not incorporated	17,102
Derler et al. [62]	Drop impact	24.5	3.1	5	Silicon elastomer	20	Not defined	Not defined	Not measured
	Drop impact	49.1	3.1	10	Silicon elastomer	20	Not defined	Not defined	7079
	Drop impact	74.6	3.1	15	Silicon elastomer	20	Not defined	Not defined	Not measured
van Schoor et al. [42]	Drop impact	19.6	1.25	25	Blue CONFOR foam	12.7	Not defined	Not incorporated	3998
	Drop impact	19.6	1.25	25	Blue CONFOR foam	24.5	Not defined	Not incorporated	6378
Bulat et al. [34]	Drop impact	26	2.5	8	Polyethylene foam	5	Not defined	Not incorporated	17,000
Laing and Robinovitch [44]	Pendulum	14, 56, 126, and 224	1, 2, 3, and 4	28	Polyethylene foam + open-cell ester foam + gum rubber	2.4	12.5	42.2	1000, 2000, 3000, 3900
	Pendulum	126	3	28	Closed-cell expanded ethylene vinyl acetate foam	30	12.5	42.2	2900
	Pendulum	14	1	28	Polyurethane, copolymer, ethylene vinyl acetate, polyethylene, and polystyrene foam	2.4	6.5, 8.2, 16.2, 31.7, and ∞	42.2	1200–1400
Holzer et al. [28]	Drop impact	50	4.5	5	Not incorporated	Not incorporated	Not incorporated	Not incorporated	6378
Choi et al. [45]	Same hip impact simulator as Laing and Robinovitch [44]								
Stewaradachpisal et al. [41]	Drop impact	24	3	4.75	Silicone	16	Not defined	Not incorporated	5561
Zhang et al. [63]	Drop impact	4.25	2.3	1.608	Nil	Nil	Nil	Nil	3700

Table 1 (continued)

Article	Type of rig	Impact energy (J)	Impact velocity (m/s)	Effective mass (kg)	Material of soft tissue	Thickness of soft tissue (mm)	Stiffness of soft tissue on GT (kN/m)	Effective stiffness of pelvis (kN/m)	Peak impact force (unpadded) (N)
Li et al. [15]	Pendulum	17	2.6	5	Sponge	10	Not incorporated	Not incorporated	5939
Lee et al. [23]	Drop impact	25	2	13	Soft, flexible foam	30	Not defined	Not defined	2350
		44	2.6	13	Soft, flexible foam	30	Not defined	Not defined	5110
Harris et al. [20]	Drop impact	11.8	2.4	4	Not incorporated	Not incorporated	Not incorporated	Not incorporated	20,000
		7.8	2.7	2.1	Not incorporated	Not incorporated	Not incorporated	Not incorporated	20,000
Song et al. [74]	Drop impact	4.9	2.6	1.437	Not incorporated	Not incorporated	Not incorporated	Not incorporated	3600

secondary peak response. Specifically, Bulat et al. [34] used a drop tower rig (drop tower type 2, Table 2) that simulated only the protuberance of the trochanter as the impact area, similar to that of a real hip bone. The response of their test system differed greatly to the response of other test systems that employed similar impact energies because the simulated musculoskeletal structure, in this case, produced a point load rather than the distributed load usually simulated by others. Additionally, except for the drop tests of Nabhani and Bamford [38], impact energies above 100 J were used only in pendulum tests and in connection with experimental setups that simulated the stiffness and the energy absorption of the human pelvis. The summary of various test systems is given in Table 3.

Force attenuation

In the literature, the attenuation force is calculated as the percentage decrease in impact force in the padded trials compared with that in the unpadded trials [65], but different laboratories have reported significant variations in the values of biomechanical effectiveness of the same hip protector (Table 4). This variation is evident in how the result of biomechanical effectiveness of the Safehip protector performs well under the impact of 19.6 J and 120 J in van Schoor et al. [42] and Nabhani and Bamford's [38] work, respectively, but had an abysmal rating in Laing and Robinovitch's [44] assessment. Additionally, Robinovitch et al. [37] reported an 18.2% force attenuation ability for the Sahva hip protector, while Mills [39] reported 77.5% for the same protector, though using lower impact energy. However, Nabhani and Bamford [38] reported an 83.7% attenuation for the same protector using the same impact energy of 120 J as Robinovitch et al. [37]. These discrepancies may be attributed to the configuration of the test system having a direct effect on the outcome when determining the effectiveness of a hip protector [65]. This reinforces the need to appropriately standardize the testing system used to determine the effectiveness of a hip protector. Table 4 demonstrates the impact and influence of the effect of variability of the test system's ability to quantify the force attenuation provided by a hip protector. A significant negative relationship between the impact energy and the impact attenuation was observed ($r(44) = -2.46, p < 0.001$) for all test systems pooled in Table 4 for hip protectors tested by more than one researcher, attesting to the fact that the severity of impact energies adversely affects the performance of the hip protector under test [47].

Discussions

By using mechanical testing systems, researchers have been able to provide significant insights into the efficacy of a hip

Table 2 Classification of hip protectors' test rigs

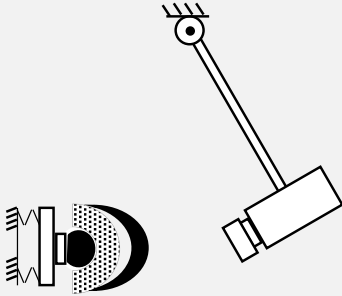
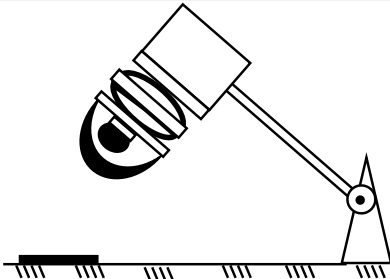
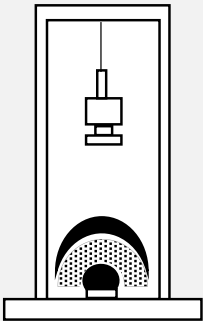
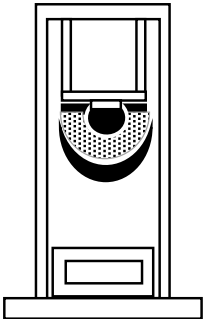
Types of Test Rig	Researchers
 <i>A: Pendulum Type 1</i>	Pendulum Type 1 without soft tissue: [35] Pendulum Type 1 with spring or bumper fixture: [35, 37, 48] Pendulum Type 1 without Spring: Nil
 <i>B: Pendulum Type 2</i>	Pendulum Type 2 with spring or bumper fixture: [45, 52] Pendulum Type 2 without Spring: [15]
 <i>C: Drop Tower Type 1</i>	Drop Tower Type 1 with spring: [11] Drop Tower Type 1 without spring: [20, 23, 28, 32, 39, 40, 42, 57, 62, 63]
 <i>D: Drop Tower Type 2</i>	Drop Tower Type 2 with spring: Nil Drop Tower Type 2 without spring: [30, 34]

Table 3 Mechanical test systems in the evaluation of force attenuation

Article	Type of rig	Specific description	Performance indicator	Key finding(s)
Robinson et al. [37]	Pendulum impact type 1 rig with 35-kg effective mass	Neoprene pelvic bumper spring supports the femur with a polyethylene foam soft tissue covering the plastic femur	Measured unpadded impact vs padded impact	A horseshoe-shaped protector decreased peak trochanteric force by more than double the amount of any of the other eight pads tested Attenuation force is linearly related to the thickness of the protector
Parkkari et al. [35]	Pendulum impact type 1 rig with 39-kg impact pendulum	Hip mass of 11.3 kg, supported on elastic steel springs of $k = 75 \text{ N mm}^{-1}$, no soft tissue	Measurement of femoral impact force against fracture threshold of 2 kN	Prevention of hip fractures should be based on other ideas other than hip padding alone
Mills [39]	Drop impact rig type 1 Impacted by a carpeted striker of 12.3 kg in mass Measurement: load cell at femoral neck and accelerometer on striker	42-mm-diameter rod of ABS (acrylonitrile butadiene styrene) copolymer used as the femur and oil-extended jelly-like red polymer used as the soft tissue	The impulse values for modified protector versus the original protector	Biomechanical effectiveness of the most common hip protector on the market was enhanced when the thickness of the soft foam back was increased
Kannus et al. [48]	Pendulum impact type 1 and a total of 40.3 kg in effective mass Measurement: load cell on the pendulum and at the femoral neck	11.7 kg of wooden femur mounted on four steel springs ($k = 18.8 \text{ kN/m}$) and 20-mm-thick polyethylene foam was employed as the trochanteric soft tissue	Comparison of anatomically designed protectors and two available in the market	Anatomically designed energy-shunting and energy-absorbing KPH protectors can provide sufficient impact force attenuation in a sideways fall simulation in the elderly
Okuizumi et al. [40]	Drop impact test type 1 using 8.4-kg impactor	Cadaveric femora were used	Right femora were fractured without protection as a control and compared with left femora covered by the protection system	Adding a resin cover to a gel-based hip protector increased its biomechanical effectiveness from 30.2 to 46.1%
Nabhani and Bamford [38]	Drop impact type 1 using 24-kg dead weights Measurement: load cell under central pin	Hip-shaped aluminum and silicon simulate the pelvis and a layer of flesh with skin. Floor covering was also simulated	Compared a new combination hip protector design with existing designs	Hard-shell hip protector designed to be glued directly to the surface of the hip provided almost as much force attenuation (77.4%) as typical garment-based protectors Floor coverings have an essential role to play in the reduction of impact forces

Table 3 (continued)

Article	Type of rig	Specific description	Performance indicator	Key finding(s)
Wiener et al. [30]	Drop impact type 2 with no spring fixture and 9 kg in effective mass Measurement: piezoelectric film sensor	Curved wooden hip model impact surface was used in the experiment with no femur	Human fall experiment to compare force transmitted when a pad is worn	Force transmission through tested pads was below that required to fracture hips from cadavers with osteoporosis in vitro
Minns et al. [32]	Drop impact type 1 with no spring fixture	No information on the characteristic of the apparatus used in the testing of the six hip protectors in this work	Measuring the reduction in peak force transmitted to the greater trochanter by the intervention of a pad covering the greater trochanter	The work assessed the safety and effectiveness of hip protectors Mismatch between a hip protector and greater trochanter can lead to tissue damage
Lam et al. [11]	Drop impact type 1 with the pelvis arrangement mounted on 75-kN/m stiff steel spring	The use of porcine hipbone as a surrogate pelvis and a 6-mm-thick silicon rubber simulates the soft tissue	Measured unprotected impact vs protected impact	Use of a protective floor covering reduces the impact force on the hip in accidental fall
Derler et al. [62]	Drop impact type 1 with 5, 10, and 15 kg effective mass Measurement: triaxial load cell at the femoral neck, accelerometer, and high-speed camera	Use of aluminum as the artificial pelvis, linked by a ball-and-socket joint to an anatomically shaped steel femur (thigh bone) embedded in the hip-shaped surface silicon elastomer material	Validated against biomechanical data	Found pad characteristics to significantly affect biomechanical effectiveness and position of the hip protector also influenced the forces applied to the femur
van Schoor et al. [42]	Drop impact type 1 with 25 kg in effective mass Measurement: femoral neck load cell	Iliac crest made of acetal copolymer with a rigid base as pelvis and composite of E-glass/epoxy for cortical bone with 2.7-thick CF -45 Confor foam as a flesh simulant	Result confirmed the result of Kannus et al. [48]	Found pad characteristics to significantly affect biomechanical effectiveness. Hip protector with shell superior to those without
Laing and Robinovitch [52]	Pendulum type 2 with 28 kg in effective mass Measurement: femoral neck load cell and floor-mounted force plate	Use of “biofidelic” surrogate pelvis connected to the pendulum via leaf spring. Incorporates a composite femur and Evazote EV 50 foam as a soft tissue simulant	The result mimics negative findings in some clinical trial as reported by [24, 30, 75]	Impact velocity, pelvis size, and soft tissue stiffness do influence force attenuation
Sze et al. [57]	Drop impact test as shown in drop impact type 1	Adoption of conservative testing approach because there was no simulation of soft tissue or pelvis system	The result is similar to those reported by [30, 39, 48]	40% thinner and 20–50% smaller anthropometrically designed hip protector can attenuate impact force under a simulated fall condition to a level that

Table 3 (continued)

Article	Type of rig	Specific description	Performance indicator	Key finding(s)
Bulat et al. [34]	Drop impact type 2 with 8 kg in effective mass Measurement: load cell at striker	Hip-shaped striker designed by information from adult skeleton greater trochanter was used with a 5-mm layer of low-density polyethylene foam (LDPE) having a density of 0.04 g/cm ³ as soft tissue No soft tissue was used	Impact benched marked against threshold force of 3100 N	is about two standard deviations below the fracture threshold of the proximal femur of older Chinese women With a different degree of degradation, the protective properties of external hip protectors do degrade after repeated impacts
Holzer et al. [28]	Drop impact test rig type 1 with an anvil connected to a sensitive piezoelectric force measuring unit		Study using a standardized mechanical test (European Standard testing method for protective impact clothing (EN 1621-1)) on hip protectors	Absorption should be preferred to energy shunting
Choi et al. [45]	Pendulum impact type 2	It has a surrogate hip that mimics the hip geometry and local variation in soft tissue stiffness of typical elderly women	Unpadded condition vs padded condition in examining the magnitude and location of peak pressure	Biomechanical evidence of hip protectors shunting forces away from the danger zone and the performance of hip protectors depends on the positions of the protectors over the hip region
Stewartadachpissal et al. [41]	Drop impact test rig type 1 Measurement: load cell below the femoral neck	It uses a femur model made of aluminum and uses silicone as the soft tissue	Validated force attenuation in a biomechanical test rig with that from finite element method	FEM shows promises as a tool for the successful design of high-performing hip protector
Zhang et al. [63]	Drop impact test rig type 1	Excludes anatomic fixtures, the impact was on a flat Plexiglass plate	Impact detected by the sensor without buffer material against impact detected by the sensor with buffer material	Material hardness and thickness of the material have an excellent impact on the attenuation rate
Li et al. [15]	Pendulum impact type 2 with 5 kg in effective mass Measurement: high-speed camera and PRESCALE pressure film Drop impact test rig type 1	A wooden block with curvature simulates the pelvis. A sponge was used to simulate the soft tissue Biofidelic femur in anatomical hip model with 30 mm of surrogate soft tissue made of soft, flexible foam	Unpadded impact on concrete floor measured against all other conditions such as different types of floor materials and hip protectors Comparison of unpadded impact with padded impact	Use of tatami matting as a flooring material is an effective strategy to prevent hip fractures Identification of optimal thickness of shear thickening polymer needed in combination

Table 3 (continued)

Article	Type of rig	Specific description	Performance indicator	Key finding(s)
Harris et al. [20]	Drop impact rig type 1 with flat and ball impactor	No femur or soft tissue, pure mechanical test with a rounded ball impactor to simulate the trochanter	Peak force transmitted compared against fracture threshold	hip protector for maximum force attenuation Shear-thickening fluid is found to be effective in improving the performance of hip protectors
Song et al. [74]	Drop impact type 1 with a 1.437-kg impactor Measurement: piezoelectric sensor on the base plate	Mechanical test with an impact between a flat base plate and a flat top plate without femur or soft tissue	Recorded forces in the unpadded condition against the padded condition	Buffer rate is found to be mostly dependent on the hardness of the sponge materials, and the total area of the orifice(s) for the leak-allowed air cushions

protector in the prevention of hip fracture, by subjecting hip protectors and surrogate femurs to higher impact forces, which are not feasible with in vivo testing because of ethical and practical considerations [43]. The attenuated forces provided by hip protectors indicate the protective value of each protector, as there is an apparent difference between the magnitudes of impact forces with and without the hip protector, which remains the sole technique of determining the pass criteria for a hip protector since no clinical trial has established any one hip protector as a gold standard [33].

The observed variation in the results of the effectiveness of the same external hip protector by different research groups is found to be a function of the representation of the test systems and the condition of impact. Some research groups represented the test system as a simplification of human anatomy [35, 38, 45, 49, 52, 62], while others aimed at producing fracture-causing events [23, 28, 34, 39]. Pinilla et al. [66] and Courtney et al. [13] investigated isolated femora in a geometrical configuration using quasi-static experiments (loading rate of 100 mm/s). Pinilla et al. [66] found fracture forces of 3.82 ± 0.91 kN for 81 ± 7 -year-old femora, while Courtney et al. [13] reported fracture loads of 4.16 ± 1.59 kN for 73 ± 8 -year-old bones, setting comparable threshold force values for femoral fracture and corresponding the applied loads to vertical forces on the greater trochanter [62]. Measured impact forces and forces transmitted to the femur of the anatomical hip model are usually compared with the fracture loads of human femora.

In the design of most systems, considerations have been given to the findings of Feldman and Rabinovitch [67] and van den Kroonenberg et al. [46] for impact velocity during unexpected sideways falls. The works of Pinilla et al. [66] and others [13, 50, 68, 69] are often considered in the determination of forces required for hip fracture, as is the work of van den Kroonenberg et al. [46] for the selection of effective mass. However, as important as the soft tissue thickness and stiffness are, there has been little or no information on the methods used by researchers to create soft tissue simulants in the literature. However, there have been suggestions that soft tissues were custom-made, adjusted, or hip-shaped by cutting, carving, molding, wrapping, and CNC machining [15, 30, 32, 34, 38, 39, 42, 49, 62].

Several studies compared their results with those reported in the literature as validation. It is opined that this could form secondary validation whenever possible. Primary validation should be based on a comparison of empirical/numerical findings to findings using cadaveric tissue at body temperature or comparison to an already validated study. Additionally, it is vital to consider surrogates of tissues at different temperatures, since temperature does significantly affect the stiffness of the polymers used, before incorporating such surrogates into a test system [70].

Table 4 Force attenuation provided by various hip protectors tested by different researchers

Pad	Impact energy (J)	Unpadded impact (N)	Impact to GT (N)	Percentage attenuation (%)	Reference
Safety Pants (FI)	120	5810	3900	32.9	Robinovitch et al. [37]
	41	3740	790	78.9	Kannus et al. [48]
	74	6130	2760	55	
	110	9190	5770	37.2	
	19.6	3998	2330	41.7	van Schoor et al. [42]
	19.6	6378	5186	18.7	
	50	NI	22,000		Holzer et al. [28]
Sahva	120	5810	4750	18.2	Robinovitch et al. [37]
	24.1	3910	880	77.5	Mills [39]
	120	4300	700	83.7	Nabhani and Bamford [38]
	19.6	3998	1298	67.5	van Schoor et al. [42]
	19.6	6378	2061	67.7	
KPH1	78	5590	1040	81.4	Parkkari et al. [73]
	132	10,400	1810	82.6	
	41	3740	590	84.2	Kannus et al. [48]
	74	6130	780	87.3	
	110	9190	1360	85.2	
	50	NI	43,000		Holzer et al. [28]
KPH2	41	3740	510	86.4	Kannus et al. [48]
	74	6130	760	87.6	
	110	9190	1170	87.3	
	19.6	3998	804	79.9	van Schoor et al. [42]
	19.6	6378	900	85.9	
	56	1392	814	41.5	Laing et al. [65]
	126	2100	1331	36.6	
	224	2698	2077	33.0	
Safehip Classic	41	3740	1080	71.1	Kannus et al. [48]
	74	6130	2240	63.5	
	110	9190	4640	49.5	
	120	4300	820	80.9	Nabhani and Bamford [38]
	19.6	3998	911	77.2	
	19.6	6378	1817	71.5	van Schoor et al. [42]
	50	NI	30,000		
	126	2000	1782	10.9	
	56	1392	1122	19.4	Laing et al. [65]
	126	2100	1733	17.5	
	224	2698	2477	8.2	
Safehip soft	126	2000	1584	20.8	Laing and Robinovitch [44]
	54.9	1275	1020	20.0	
	56	1392	919	34.0	Choi et al. 2010
	126	2100	1541	26.6	
	224	2698	2193	18.7	
Hipsaver	19.6	3998	1689	57.8	van Schoor et al. [42]
	19.6	6378	3472	45.6	
	126	2000	1582	20.9	Laing and Robinovitch [44]
	54.9	1275	710	45	
	56	1392	1063	23.6	Choi et al. [45]
	126	2100	1607	23.5	
	224	2698	2223	17.6	

Apart from the methodological issues of soft tissue thickness and stiffness mentioned above, there are more barriers to the objective determination of the biomechanical effectiveness of hip protectors, including effective mass, impact velocity, valid pelvic stiffness, trochanteric soft tissue material, peak compressive force, time to peak compressive force, filtering force signals, and material selection for various parts of the model. To improve the understanding of the properties of impacted tissues under impact conditions, further exploitation with finite element analysis (FEA), and using better data for the soft tissue properties, would help simulate the load shunting properties of protectors just as FEA contributes to the understanding of the region that experiences the highest stress in a fall [71].

While there is observed variability in the influence of the impact energy employed by the various studies as shown by the reported correlation result, there exists agreement in most of the studies in this review to the effect of the surface topography of the soft tissue in the hip region as evident in the representation of the soft tissue surface as being curved. Simulating fall incidence with the various test systems, test protocol, and surrogate musculoskeletal structures explains the wide range of values for peak femoral forces and the corresponding percentage of impact attenuation reported for the same hip protector by different researchers.

The results from this systematic review show that the hip protector is a probable intervention for impact attenuation and could have substantial benefits in reducing hip fracture, although reaching an objective point on the magnitude of the impact attenuation is subject to further research and standardization of the test systems with an emphasis on femur/pelvis surrogate geometry and materials for the transmission of impact forces. Robinovitch et al. [33] gave a consensus statement on recommended techniques for evaluating the biomechanical performance of hip protectors by the International Hip Protector Research Group following a meeting in Copenhagen in November 2007 concerning the lack of unifying and agreeable techniques in evaluating the effectiveness of hip protector. They opined that “the primary outcome of testing should be the percentage reduction (compared with the unpadded condition) in the peak value of the axially compressive force applied to the femoral neck during a simulated fall on the greater trochanter. To provide consistent results test system should accurately simulate the pelvic anatomy, and the impact velocity (3.4 m/s), pelvic stiffness (acceptable range: 39–55 kN/m), and effective mass of the body (acceptable range: 22–33 kg) during impact. Given the current lack of clear evidence regarding the clinical efficacy of specific hip protectors, the primary value of biomechanical testing at present is to compare the protective value of different products, as opposed to rejecting or accepting specific devices for market use.”

In the same report, Robinovitch et al. [33] acknowledged that other issues influencing the overall value of hip protectors include their ability to reduce peak force in older men, their ability to reduce peak forces over a range of fall directions, and their ability to reduce the peak magnitude of the components of the load at the proximal femur other than axial compression (such as bending and torsional moments and shear forces). Others are the durability of the protector to repeated laundering (or repeated impacts), the potential for movement of the protector from its intended location, and the effect of variations in temperature and humidity on the provided force reduction. The risk for skin damage related to prolonged use and movement over exposed skin and esthetic factors related to device thickness, garment design, and patient acceptance were also stated. These issues set a clear direction toward achieving optimized hip protectors in preventing a hip fracture.

It is therefore crucial for researchers to aim at improving the understanding of the dynamics of falls and the factors that govern force development. Conceivably, the mechanical properties and functional anatomy of the soft tissues and musculoskeletal structures surrounding the hip region, especially in vulnerable populations, are of specific interest. The variations in human anatomy may require testing on average human simulations to achieve higher objectivity and realistic biomechanical examinations. Research in this area should champion further refinement of hip protector test systems and methods, leading to the development of more clinically effective products. Finally, as Table 4 demonstrates that some hip protectors are consistently better than others across multiple test systems, criteria can be developed for external hip protectors for clinical trials. Hence, the principal assessment of biomechanical testing remains the comparison of the protective effects of new and existing hip protectors using a test system that incorporates the attributes articulated by the Copenhagen Consensus Conference [33].

Conclusion

Dissimilarities between test systems’ characteristics, employed surface geometries, inherent mechanical properties, and magnitudes of impact energy employed in determining the effectiveness of hip protectors account for the variability in test results [44, 47, 53, 65, 72]. Therefore, a consensus standard on a test system that incorporates the attributes articulated by the Copenhagen Consensus Conference is highly needed to ensure repeatability and comparison. This measure will help establish the standard efficacy of an external hip protector that could be validated by computational techniques such as finite element modeling before further in-depth clinical trials using mechanically tested hip protectors to establish the validity of outcomes on the various interventions. It is expected that this information will be invaluable to product developers, clinicians, and other

researchers seeking to improve or optimize hip protectors for effective prevention of hip fracture and avoidance of its accompanying, worrisome costs.

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Compliance with ethical standards

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