SYSTEM FOR REDIRECTING HEAD IMPACT FORCE

Applicant: Board of Trustees of the Leland Stanford Junior University, Palo Alto, CA (US)

Inventors: Fidel Hernandez, Palo Alto, CA (US);
Kaveh Laksari, Palo Alto, CA (US);
David B. Camarillo, Palo Alto, CA (US)

Appl. No.: 14/619,748

Filed: Feb. 11, 2015

Related U.S. Application Data

Provisional application No. 61/938,493, filed on Feb. 11, 2014, provisional application No. 62/096,727, filed on Dec. 24, 2014.

Publication Classification

Int. Cl.
A42B 3/04 (2006.01)
A41D 13/05 (2006.01)
A63B 7/10 (2006.01)

U.S. Cl.
CPC ............................ A42B 3/0473 (2013.01); A63B 7/10 (2013.01); A41D 13/0512 (2013.01)

ABSTRACT

Described herein is a system for redirecting head impact force to other portion or portions of a body of a person. The system includes a harness wearable on upper body or both upper and lower body of the person and permitting motion of the person; a force redirecting element configured to connect the harness to a helmet wearable by the person; and a motion limiting unit connected to the force redirecting element, wherein the motion limiting unit can be triggered by the impact and limit the load on the neck of the person. The system also includes stiffening units to pre-tension the harness and increase the effective impedance of the system.
FIG. 1A

Impact

FIG. 1B

Lateral Head Acceleration (g)

Helmet
Helmet + Cable Restraint

Coronal Rotational Velocity (radian/s)

Time (S)
FIG. 1C

Compression Limit, 4.6 kN
(Eppinger 1999)
FIG. 2A

FIG. 2B
FIG. 3
SYSTEM FOR REDIRECTING HEAD IMPACT FORCE

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/938,493 filed on Feb. 11, 2014, and U.S. Provisional Application Ser. No. 62/096,727 filed on Dec. 24, 2014, the disclosures of which are incorporated herein by reference in their entireties for all purposes.

FIELD OF THE DISCLOSURE

[0002] The present disclosure, in general, relates to a system for redirecting the head impact force to other parts of the body to reduce risks of head and neck injury.

BACKGROUND

[0003] The following discussion of the background of the disclosure is merely provided to aid the reader in understanding the disclosure and is not admitted to describe or constitute prior art to the present disclosure.

[0004] Head injuries arise from damaging forces applied directly to the head or to the body that result in a rapid acceleration of the head. The resulting translation and rotation of the head and neck may be associated with neurological outcomes associated with brain injury. Brain injury may occur due to either (1) focal trauma from concentrated forces causing a rapid, focal translational acceleration that may lead to skull fracture or deformation that impinges on the brain, a severe form of traumatic brain injury (TBI); or (2) diffuse trauma from acceleration that causes inertial loading deep within the brain. Mild TBI (mTBI) is mostly associated with the rotation of brain that produces neuronal damage in shear.

[0005] TBI has been identified as a major public health concern by the U.S. Center for Disease Control and Prevention, and is a leading cause of death and disability worldwide. Most of these injuries are caused by falls, motor vehicle collisions, sports activity, recreation, and violence. mTBI accounts for about 75% of all reported TBI incidents. It is estimated that about 1.6 to 3.6 million sports-related mTBIs are diagnosed each year in the United States.

[0006] Therefore, a system is needed to reduce the head acceleration resulting from a damaging force to the head or body, thus reducing the risk of mTBI without increasing the risk of other types of head and neck injury.

SUMMARY

[0007] The present disclosure provides, in some embodiments, a system for redirecting head impact force to other portion or portions of a body of a person, the system comprising: a harness wearable on the body of the person and permitting motion of the person; a force redirecting element configured to connect the harness to a helmet wearable by the person; and a motion limiting unit connected to the force redirecting element, wherein the motion limiting unit is configured to be activated by motion of the force redirecting element, and limit a force applied by the force redirecting element to within a threshold level.

[0008] In some embodiments, the harness of the system is configured to be tightened around the body on at least one of the upper arm, forearm, abdomen, chest, waist, thigh, pelvic bone, hip, elbow, knee, and foot of the person.

[0009] In some embodiments, the harness of the system comprises at least one adjustable strap for tightening the harness to the body.

[0010] In some embodiments, the harness of the system holds at least one end of the force redirecting element on the body at, or in the vicinity of, one of the abdomen, chest, waist, thigh, pelvic bone, hip, knee, and foot of the person.

[0011] In some embodiments, the harness of the system includes a body garment. In some embodiments, the body garment comprises a fabric with a reinforcement structure. In some embodiments, the harness of the system includes straps configured to wrap around the body.

[0012] In some embodiments, the motion limiting unit of the system is a retractor.

[0013] In some embodiments, the force redirecting element of the system includes at least one of a spring, a damper, a strut, a cable, and an inflatable element.

[0014] In some embodiments, the force redirecting element of the system is a cable assembly including: an inner cable; an intermediate layer surrounding the inner cable and configured to allow the inner cable to move relative to the intermediate layer; and an outer layer embedded with a helical metallic structure, the outer layer covering at least a portion of the intermediate layer.

[0015] In some embodiments, the force redirecting element of the system is at least partially embedded in the harness or at least partially runs under the harness.

[0016] In some embodiments, the system for redirecting head impact force further comprises a plurality of force redirecting elements configured to connect the helmet to the harness at different locations on the harness. In some embodiments, at least one of the plurality of force redirecting elements is connected to the harness at or below a waist of the person. In some embodiments, the system further comprises a plurality of motion limiting units each connected to a respective one of the plurality of force redirecting elements.

[0017] The present disclosure also provides, in some embodiments, a system for redirecting head impact force to other portion or portions of a body of a person, the system comprising: a harness configured to connect to the body of the person and permit motion of the person; and a force redirecting element configured to connect the harness to a helmet wearable by the person, wherein the harness is configured for tightening around the body at least at or below a waist of the person.

[0018] In some embodiments, the force redirecting element of the system is connected to the harness at or below the waist of the person.

[0019] In some embodiments, the system for redirecting head impact force further comprises a motion limiting unit connected to the force redirecting element.

[0020] In some embodiments, the system for redirecting head impact force further comprises a plurality of force redirecting elements configured to connect the helmet to the harness at different locations on the harness.

[0021] The present disclosure also provides, in some embodiments, a system for redirecting head impact force to other portion or portions of a body of a person, the system comprising: a harness configured to connect to the body of the person and permit motion of the person; a force redirecting element configured to connect the harness to a helmet wearable by the person; and a stiffening unit configured to pre-tension the harness to increase an effective impedance of the body of the person.
In some embodiments, the stiffening unit in the system for redirecting head impact force includes one or more springs and dampers each attached to two points on the harness. In some embodiments, the stiffening unit includes a padding under the harness. In some embodiments, the padding is under shoulder straps of the harness. In some embodiments, the stiffening unit is configured to be triggered by the head impact force.

Other aspects and embodiments of the disclosure are also contemplated. The foregoing summary and the following detailed description are not meant to restrict the disclosure to any particular embodiment but are merely meant to describe some embodiments of the disclosure.

**BRIEF DESCRIPTION OF DRAWINGS**

- FIG. 1A illustrates a head-neck musculoskeletal model with a restraint cable.
- FIG. 1B illustrates the comparison of linear acceleration (left axis, solid lines) and rotational velocity (right axis, dashed lines) caused by impacts in unrestrained (upper lines) and restrained (lower lines) configurations.
- FIG. 1C demonstrates the dumping properties of a system can be optimized to keep neck compression forces within a tolerable threshold level, such as about 4.5 KN.
- FIG. 2A illustrates an anthropomorphic test device (ATD) impact test setup with a linear impactor and a stiff restraint attached to a helmet.
- FIG. 2B illustrates the reduction in anterior head acceleration with exo-skeleton restraint.
- FIG. 3 illustrates the measurement results of the tendon acceleration during voluntary coronal head rotation.
- FIG. 4 depicts an embodiment of a restraint system for redirecting impact forces from the head to the torso of a person.
- FIG. 5 illustrates an embodiment of a force redirecting element in the form of a multi-layer cable.
- FIG. 6 depicts another embodiment of the restraint system based on a modified shoulder pad system for redirecting impact forces from the head to the torso of a person.
- FIG. 7 depicts another embodiment of the head impact force redirecting system where the harness includes straps wrapping around the body of a person, and the force redirecting element also wraps around the body.
- FIG. 8 depicts an embodiment of the head impact force redirecting system where the harness is a body garment.
- FIG. 9 depicts an embodiment of the head impact force redirecting system where the harness includes straps wrapping around the body, and the force redirecting elements are at least partially embedded in the straps or at least partially run under the straps.
- FIG. 10 depicts an embodiment of the head impact force redirecting system where the harness includes straps wrapping around the body of a person down to the feet, and the force redirecting elements are at least partially embedded in the straps or at least partially run under the straps.
- FIG. 11A illustrates a setup form quasi-static characterization of a body harness.
- FIG. 11B illustrates the measurement result of impact force versus displacement of a body harness relative to the head.
- FIG. 12 illustrates a harness with pre-tensioning or stiffening units in the form of tensioned springs.
- FIG. 13 illustrates a harness with pre-tensioning or stiffening unit in the form of ribbing, boning, or metallic mesh embedded in the harness.

**DETAILED DESCRIPTION**

To reduce the incidence of fatalities and severe TBI, helmets are designed with the goal of reducing the amplitude and duration of translational acceleration. Two basic principles are employed in helmets. First, a rigid outer shell spreads a contact force over a larger area on the helmet and the head, thereby reducing stress on the skull. Second, an inner padding material deforms during collision, which lengthens the time of the impulse while reducing the maximum force.

Focal brain trauma is largely a solved issue today as helmets can effectively distribute concentrated forces. However, because mTBI and severe TBI have different physical injury mechanisms, modern shell helmets are not sufficient to address both forms of TBI. While reported cases of severe TBI have been dramatically reduced, diffuse inertial injury appears to be on the rise despite the use of helmets. The starkest example is in American football, where about 200,000 concussions were reported in 2009 among about 5 million helmeted players.

The level of forces that persist in football, warfare, and cycling is clearly too high for a human head to resist to prevent acceleration injury. Even with an ideal helmet material that maintains a constant force during deformation, there is a practical limitation because a wearable helmet has to be of certain thickness. A second fundamental limitation of helmets is that the force reduction using a helmet is achieved by extending the impulse duration, which is worse for inertial loading of the brain because the longer a given acceleration is held, the further it can penetrate into the brain. Therefore, an ideal solution to the problem would reduce both acceleration amplitude and duration.

Improvements in materials and testing standards of helmets in the 20th century have nearly eliminated skull fracture and focal injury in American football. However, as discussed above, using helmets to reduce the contact force on the head has its practical and theoretical limitations, ultimately relying on the neck to do the critical work to prevent diffuse injuries caused by inertial acceleration. But the human neck is one of the weakest links on the body. The added weight of the hard shell helmet further stresses the neck such that the risk of mTBI is greater.

Among primates, humans have the smallest neck to head area ratio. The relatively weak human neck is ineffective at restraining head acceleration during collision. Primates with larger necks are more resistant to diffuse brain injury, and primates equipped with a restraining neck collar show dramatically increased tolerance to collision. When exposed to high energy impacts, the 5 Kg human head is susceptible to...
inertial injury unless the neck is augmented with a restraint system that can restrain head acceleration while not impeding normal voluntary motion.

[0048] The neck musculature may not be able to provide sufficient force to reduce acceleration amplitude and duration in many scenarios. The restraint system in some embodiments of the present disclosure acts to augment the neck muscles, redirect the damaging force from the head to the upper and lower body of the person, thus increase the effective weight and stiffness of the support for the head to reduce both acceleration amplitude and duration. In some embodiments, the restraint system can be pre-tensioned to further increase the effective stiffness and impedance of the restraint system.

[0049] While some restraint systems can be used to redirect the damaging force to the head to reduce the acceleration of the head that could produce mTBI, they could load the neck with compression force, which could result in compressive force on the cervical spine and could have damaging effects that produce other forms of injury. Therefore, tension in the restraint system should be maintained within safe levels.

[0050] In some embodiments of the present disclosure, an acceleration and force restraint system that allows for normal voluntary motion of a human body and does not cause a secondary injury is disclosed. Also disclosed is an approach for selectively restraining head motion by transferring force to the torso using a restraint system controlled by a mechanism that can be triggered by at least one of an acceleration, a velocity, and a force.

[0051] The restraint system disclosed in the present disclosure can prevent diffuse brain trauma while (1) reducing impulsive acceleration amplitude and duration, (2) permitting voluntary movement, and (3) maintaining safe cervical spine compression loads below the injury level. The restraint system allows normal motion at low accelerations; locks at pre-defined injury-prone accelerations, velocities or forces; and has a force threshold level to protect the neck and the cervical spine.

[0052] The restraint system disclosed herein augments the neck by redirecting the force of an impact to the human body, thus redirecting the load carried by the head and neck to the shoulders, torso, or other anatomical structures that can carry the added load without injury, and allowing the human body to absorb energy in addition to the helmet materials to protect the head using the larger inertia of the human body itself.

[0053] According to Newton’s second law of motion, the force applied on an object is equal to the product of the acceleration of the object and the mass of the object. Impedance of an object can be represented by the ratio of force over deformation velocity. Thus, a heavier and stiffer object has a higher impedance and less acceleration compared with a lighter object when the same force is applied to both objects. For this reason, a full body has a higher resistance to acceleration than a head or an upper body. Thus, it is advantageous to redirect the impact force from the head and the neck to the full body.

[0054] The effect of force redirection from the head through a restraint cable is illustrated in FIGS. 1A-1C by the simulation results of an ideal helmet with and without a restraint cable. FIG. 1A is a head-neck musculoskeletal model with a restraint cable 104. The helmet padding is modeled by an ideal spring 106 that is tuned to be just soft enough to displace by the entire helmet thickness while preventing head-mass contact. The restraint cable 104 locks at an acceleration of two standard gravities, and acts rigidly until the load it carries reaches a 4 KN limit, after which it maintains constant load force. In the simulation, the head 102 collides with an object (not shown) weighted 7.5 Kg at a speed of 7.5 meter per second (m/S).

[0055] FIG. 1B illustrates the comparison of the linear acceleration (left axis, solid lines) and the rotational velocity (right axis, dashed lines) caused by the impact in unrestrained (upper lines) and restrained (lower lines) configurations. Line 112 illustrates the lateral head acceleration caused by the impact in the unrestrained configuration as a function of time. Line 114 illustrates the lateral head acceleration caused by the impact in the restrained configuration as a function of time. Line 116 illustrates the coronal rotational velocity caused by the impact in the unrestrained configuration as a function of time. Line 118 illustrates the coronal rotational velocity caused by the impact in the restrained configuration as a function of time. The simulation results indicate that the restraint cable can reduce the peak linear acceleration by about 25% and the peak angular velocity by about 52%, without extending the impulse duration.

[0056] FIG. 1C illustrates the axial neck force during the impact. Line 122 illustrates the axial neck load in the unrestrained configuration, and line 124 illustrates the axial neck load in the restrained configuration. FIG. 1C demonstrates that the damping properties of a force redirecting element can be optimized to keep neck reaction forces within the tolerable compression level, such as about 4.5 KN. A finite element simulation of the brain during the head acceleration upon impact also confirms about 12% reduction in shear strain.

[0057] FIG. 2A illustrates an AITD impact test setup with a linear impactor 208 and a stiff restraint 206 attached to a dummy head (helmet) 202 on a Hybrid III neck 204. The restraint 206 is connected to a 150 Kg mass and the impactor is at a speed of 4.2 m/S.

[0058] FIG. 2B illustrates the measurement results of anterior head acceleration using the setup illustrated in FIG. 2A. Curve 212 represents the head acceleration during the impact in the configuration without the restraint 206, while curve 214 represents the head acceleration during the impact in the configuration where restraint 206 is connected to the helmet 202. The results in FIG. 2B suggest that the acceleration and impulse duration are both reduced with the exo-skeletal restraint.

[0059] Experimental results also indicate that voluntary head accelerations are much lower than head accelerations in collisions, as depicted in FIG. 3, which illustrates the head kinematics of a person exerting maximum neck muscle eccentric contraction by rotating the head at maximum speed from neutral position in three anatomical planes (anterior/ posterior, medial/lateral, and superior/inferior axes). The experiments can be carried out using markers and cameras for motion capture, or accelerometers positioned on the helmet. The measurement results show that the helmet acceleration levels remain below two standard gravities in all three anatomical planes. Thus, voluntary head accelerations can be distinguished from those caused by collisions. Therefore, accelerations can be used as the criteria to differentiate voluntary motions from impact conditions by a locking mechanism to reduce, dampen, or stop accelerations caused by impacts.

[0060] Alternatively, velocities and forces can be used as the criteria to differentiate voluntary motions from impact
conditions. For example, a locking mechanism based on centrifugal forces can be employed to reduce, dampen, or stop motions caused by impacts.

[0061] In some embodiments, as depicted in FIG. 4, the head impact force redirecting system includes (1) a plurality of force redirecting elements 404 configured to connect to a helmet 402 at one end of each of the plurality of force redirecting elements 404; (2) a plurality of motion limiting units 410 connected to the other end of each of the plurality of force redirecting elements 404; and (3) a body harness 408 that holds down at least one end of each of the force redirecting elements 404 to the body 400 of a person. In some embodiments, at least one force redirecting element 404 is at least partially enclosed in a housing 406. In some embodiments, the body harness 408 includes straps that wraps around shoulders and under arms.

[0062] In some embodiments, the force redirecting elements transfer the force caused by rotational accelerations and linear accelerations of the helmet worn on a head of a person to the torso to reduce the rotational accelerations and linear accelerations of the head.

[0063] In some embodiments, the force redirecting elements include at least one of a spring, a damper, a strut, a tether, and an inflatable element. FIG. 5 illustrates one embodiment of the force redirecting element 500 in the form of a Bowden cable assembly. In the embodiment illustrated in FIG. 5, the force redirecting element 500 includes an inner cable 502 for redirecting force from one end of the inner cable 502 to the other end of the inner cable 502; an intermediate layer 504 surrounding the inner cable 502; and an outer layer 506 formed by a helical supporting structure 508 (e.g., a helical metallic structure) embedded in a soft rubber coating. The force redirecting element 500 in FIG. 5 can take a curvy path wrapping around the body of a person.

[0064] The outer layer 506 of the force redirecting element 500 depicted in FIG. 5 can maintain its shape due to the embedded helical metallic structure 508. The outer layer 506 can be held at least one location of the body of a person. The intermediate layer 504 can be formed of a low-friction material, such as plastic, and is separated from the inner cable 502 such that the inner cable 502 can move axially within a tube formed by the intermediate layer 504 when being pulled from either end. The inner cable 502 depicted in FIG. 5 can be a stiff cable made of materials of high tensile strength, such as steel, steel alloy, carbon fiber, glass fiber and carbon nanotube. The inner cable 502 can be attached to a helmet wearable by a person on one end, and attached to a motion limiting unit on the other end to redirect a force from the helmet to the torso of the person.

[0065] Referring back to FIG. 4, in some embodiments, the motion limiting unit 410 can be securely connected to the harness 408 or held to the body 400 of the person by the harness 408. In some embodiments, the motion limiting unit 408 can be connected to one force redirecting element 404. In some embodiments, the motion limiting unit 408 can be located between two force redirecting elements 404 and connect the two force redirecting elements 404 together by connecting to one end of each of the two force redirecting elements 404.

[0066] In some embodiments, the motion limiting unit is a retractor mechanism, such as a spool mechanism. In some embodiments, the motion limiting unit can be a disk brake. In some embodiments, the motion limiting unit can be mechanically or electro-mechanically triggered (such as through a mechanical or electro-mechanical triggering mechanism) by an acceleration of the force redirecting element attached to the motion limiting unit when the acceleration of the force redirecting element exceeds a minimum threshold level. In some embodiments, the motion limiting unit can be mechanically or electro-mechanically triggered (such as through a mechanical or electro-mechanical triggering mechanism) by a velocity of the force redirecting element attached to the motion limiting unit when the velocity of the force redirecting element relative to the motion limiting unit exceeds a minimum threshold level. Alternatively, or in conjunction, the motion limiting unit can be mechanically or electro-mechanically triggered (such as through a mechanical or electro-mechanical triggering mechanism) by the force applied to the motion limiting unit by the force redirecting element connected to it when the force applied exceeds a minimum threshold level. When triggered, the motion limiting units can slow, dampen, or stop the motion of the force redirecting element connected to it, so as to slow, dampen, or stop the movement of the helmet, and therefore the head, relative to the torso of the person.

[0067] In some embodiments, the motion limiting unit is capable of pre-tensioning the force redirecting element to reduce slack in the force redirecting element, and therefore increase the effective impedance of the restraint system, and reduce the response time of the restraint system in case of collisions.

[0068] In some embodiments, when the force applied to the motion limiting unit by the force redirecting element exceeds a maximum threshold level, such as, for example, about 4.5 KN, the force redirecting element can be released, or disengaged, from the motion limiting unit to avoid unsafe compressive load on the neck and the cervical spine. In some embodiments, the force redirecting element can be re-engaged with the motion limiting unit after the release or disengagement to reduce cost. In some embodiments, the motion limiting unit can maintain the force applied by the force redirecting element within a maximum allowed level without releasing the force redirecting element.

[0069] In some embodiments, as illustrated in FIG. 6, the harness 600 can be a modified shoulder pad system similar to one worn by a football player. In FIG. 6, the harness 600 includes protective shields, such as shoulder pads 604, chest pads 608 and back pads 616, and straps 614 connecting these pads and affixing the pads to the body of a person. In some embodiments, the harness 600 also includes a neck protection plate 610. In these embodiments, retractors 606 can be attached to at least one of the chest pads 608, back pads 616, and shoulder pads 604. A cable 612 connects the retractor 606 on one end to a helmet 602 on the other end for transferring the force from the helmet 602 to the harness 600 and the body of the person.

[0070] In some embodiments, as illustrated in FIG. 7, the force redirecting element 708 wraps around the torso 700 without being stripped down on the torso except for portions in the vicinity of both ends of the force redirecting element 708. In some embodiments, the harness 706 include straps that wrap around the shoulder or arm 714 to hold down one end of the force redirecting element 708. In some embodiments, an inner cable 704 of the force redirecting element 708 is connected to the helmet 702 at connection point 718. In some embodiments, the harness 706 also includes straps 710 that wrap around the legs 716 to hold down the other end of
the force redirecting element 708, where the force redirecting element 708 is connected to the motion limiting unit 712.

[0071] In another embodiment as illustrated in FIG. 8, the harness includes a body garment 808. In some embodiments, the body garment 808 is made of a tight form-fitting fabric that is flexible to allow voluntary motion. In some embodiments, the fabric of the body garment is reinforced with light weight boning 810 or other supporting structures, such as ribs or stays, inserted into channels formed in the fabric. The boning 810 improves the tensile strength of the fabric, and helps to maintain the shape of the harness 808 conforming to the body. Motion limiting units 806 are affixed to the body garment 808 at different locations and connected to a helmet 802 through force redirecting elements 804.

[0072] In some embodiments, as depicted in FIG. 9, the harness includes straps 906 wrapping around the body above or below pads or jersey. Force redirecting elements 908 are at least partially embedded in the straps 906 or at least partially run under the straps 906, as shown by the dotted lines, and are connected to a helmet 902 through cables 904. In some embodiments, the harness also includes at least one adjustable strap 910 for holding the harness to the body. In some embodiments, the straps 906 wrap around the legs and are connected to motion limiting units 914 located on the leg. In some embodiments, the motion limiting units 914 are held to the legs by bracings 912, which can also hold the straps 906 to the legs. In some embodiments, the motion limiting units 914 are held to the legs by the straps 906.

[0073] In some embodiments, as depicted in FIG. 10, the harness includes straps 1006 wrapping around the body above or below protection pads or jersey 1010. Force redirecting elements 1008 are at least partially embedded in the straps 1006 or at least partially run under the straps 1006, as shown by the dotted lines, and are connected to a helmet 1002 through cables 1004. In some embodiments, the harness also includes at least one adjustable strap 1012 for holding the harness to the body. In some embodiments, the straps 1006 run along the legs to the feet and are connected to motion limiting units 1014 located around the feet.

[0074] In some embodiments, as illustrated in FIGS. 7-10, at least one motion limiting unit is affixed at or below a waist of the body such that when the force redirecting element connected to the motion limiting unit is pulled by an impact force, the lower body, such as the waist, legs, and feet, can bear the force. For example, in the embodiment shown by FIG. 7, the motion limiting units 712 and the force redirecting elements 708 are held to the legs by mechanisms such as under-leg straps 710. In the embodiment shown by FIG. 8, at least one motion limiting unit 806 is affixed to the body garment 808 at or below the waist, by mechanisms such as a belt or strap 812.

[0075] In some embodiments, as illustrated in FIGS. 4 and 6-10, the restraint system includes a plurality of force redirecting elements, such as restraint cables, each connected to one of a plurality of motion limiting units, such as spools. The plurality of motion limiting units can be connected to the harness at different locations on the harness, such as shoulders, chest, back, waist, abdomen, thighs, pelvic bone, hips, knees or feet of a person, to distribute the force in a larger area around the body. In some embodiments, the motion limiting units can be arranged in multi-stage, such as being connected in series by multiple force redirecting elements, to distribute force in a larger area around the body.

[0076] The human body has a higher resistance to acceleration than the head. However, this impedance is finite. The effective impedance of the human torso to impact force is further reduced if there is relative displacement between the harness and the human torso during impact. The coupling of harness to the body should allow for rapid build-up of force and therefore should avoid slack to prevent displacement when little or no force is applied. It is thus advantageous to pre-tension the harness to eliminate or reduce slack such that it is tightly coupled to the human body at least during the impact.

[0077] FIG. 11A illustrates a setup for static loading test on a harness. In the setup, a dummy 1102 wears a body harness 1104, and a cable 1108 is inserted on the back and passes the head. The cable 1108 runs over a pulley 1106 affixed on a solid support, and runs back down on the other side 1110, where it is connected to objects of different weights. During the test, the objects are dropped from different heights. The displacement of the harness relative to the head is recorded and plotted against the force applied due to the drop of the objects, as illustrated by curve 1112 in the example in FIG. 11B. Curve 1112 in the example in FIG. 11B indicates that there is no relative displacement between the harness 1104 and the head when no or little force is applied, and therefore there is no slack. The actual measurement result depends on the type of the harness under test and how it is coupled to the body. The displacement of the harness in the example in FIG. 11B is due to the deformation of the helmet liners, the torso, or the pelvis.

[0078] In some embodiments, as illustrated in FIG. 12, a helmet 1202 is coupled to a harness 1206 through force redirecting elements 1204. The harness 1206 is pre-tensioned with pre-tensioning or stiffening units, such as pre-tensioned springs 1210 or dampers. Each of the stiffening units, such as the pre-tensioned springs 1210, is connected to the harness 1206 at various points 1208 on the harness 1206. The stiffening unit carries at least one of a compressive load and a tensile load along its axis.

[0079] In some embodiments, as illustrated in FIG. 13, the harness 1302 is in the form of a body garment, and is pre-tensioned by a metallic mesh 1304 or other stiffening structures, such as ribs or boning 1306.

[0080] In some embodiments, the harness is pre-tensioned with stiffening unit such as a padding inserted under the harness. The padding stretches the harness and provides a pre-tensioning force. In some embodiments, the padding is inserted under shoulder straps to pull the harness upwards and provide the pre-tensioning force. In some embodiments, the padding is inflatable, and can be inflated upon detection of impact. In some embodiments, the inflation of the padding can be triggered through mechanical or electro-mechanical triggering mechanism.

[0081] In some embodiments, the harness can be designed using musculoskeletal simulation. More sophisticated design can involve finite element models of the helmet, harness, skull, and brain. The design variables can include force redirecting element insertion location, number of force redirecting elements used, acceleration trigger level, force limits, and many others parameters. The design process using musculoskeletal simulation allows for a quick determination of ideal system configuration.

[0082] While the disclosure has been described with reference to the specific embodiments thereof, it should be understood by those skilled in the art that various changes may be
made and equivalents may be substituted without departing from the true spirit and scope of the disclosure as defined by the appended claims. In addition, many modifications may be made to adapt a particular situation, material, composition of matter, method, operation or operations, to the objective, spirit and scope of the disclosure. All such modifications are intended to be within the scope of the claims appended hereto. In particular, while certain methods may have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations is not a limitation of the disclosure.

[0083] As used herein, the singular terms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to an object can include multiple objects unless the context clearly dictates otherwise.

[0084] As used herein, the term “about” is used to describe and account for small variations. When used in conjunction with an event or circumstance, the term can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, the term can refer to less than or equal to ±5%, such as less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%.

[0085] While certain conditions and criteria are specified herein, it should be understood that these conditions and criteria apply to some embodiments of the disclosure, and that these conditions and criteria can be relaxed or otherwise modified for other embodiments of the disclosure.

What is claimed is:

1. A system for redirecting head impact force to other portion or portions of a body of a person, comprising:
   a harness wearable on the body of the person and permitting motion of the person;
   a force redirecting element configured to connect the harness to a helmet wearable by the person; and
   a motion limiting unit connected to the force redirecting element, wherein the motion limiting unit is configured to be triggered by motion of the force redirecting element, and limit a force applied by the force redirecting element to within a threshold level.

2. The system of claim 1, wherein the harness is configured to be tightened around the body on at least one of upper arm, forearm, abdomen, chest, waist, thigh, pelvic bone, hip, elbow, knee, and foot of the person.

3. The system of claim 1, wherein the harness comprises at least one adjustable strap for tightening the harness to the body.

4. The system of claim 1, wherein the harness holds at least one end of the force redirecting element on the body at, or in the vicinity of, one of abdomen, chest, waist, thigh, pelvic bone, hip, knee, and foot of the person.

5. The system of claim 1, wherein the harness includes at least one of a body garment comprising a fabric with a reinforcement structure, and straps configured to wrap around the body.

6. The system of claim 1, wherein the motion limiting unit is a retractor.

7. The system of claim 1, wherein the force redirecting element includes at least one of a spring, a damper, a strut, a cable, and an inflatable element.

8. The system of claim 1, wherein the force redirecting element is a cable assembly including:
   an inner cable;
   an intermediate layer surrounding the inner cable and configured to allow the inner cable to move relative to the intermediate layer; and
   an outer layer embedded with a helical metallic structure, the outer layer covering at least a portion of the intermediate layer.

9. The system of claim 1, wherein the force redirecting element is at least partially embedded in the harness or at least partially runs under the harness.

10. The system of claim 1, further comprising a plurality of force redirecting elements configured to connect the helmet to the harness at different locations on the harness.

11. The system of claim 10, wherein at least one of the plurality of force redirecting elements is connected to the harness at or below a waist of the person.

12. The system of claim 10, further comprising a plurality of motion limiting units each connected to a respective one of the plurality of force redirecting elements.

13. A system for redirecting head impact force to other portion or portions of a body of a person, comprising:
   a harness configured to connect to the body of the person and permitting motion of the person; and
   a force redirecting element configured to connect the harness to a helmet wearable by the person,
   wherein the harness is configured for tightening around the body at least at or below a waist of the person.

14. The system of claim 13, wherein the force redirecting element is connected to the harness at or below the waist of the person.

15. The system of claim 13, further comprising a motion limiting unit connected to the force redirecting element.

16. The system of claim 13, further comprising a plurality of force redirecting elements configured to connect the helmet to the harness at different locations on the harness.

17. A system for redirecting head impact force to other portion or portions of a body of a person, comprising:
   a harness configured to connect to the body of the person and permitting motion of the person;
   a force redirecting element configured to connect the harness to a helmet wearable by the person; and
   a stiffening unit configured to pre-tension the harness to increase an effective impedance of the body of the person.

18. The system of claim 17, wherein the stiffening unit includes at least one of: (a) one or more springs and dampers each attached to two points on the harness, and (b) a padding under the harness.

19. The system of claim 18, wherein the padding is under shoulder straps of the harness.

20. The system of claim 17, wherein the stiffening unit is configured to be triggered by the head impact force.

* * * * *