SYSTEMS AND METHODS FOR MEASURING, ANALYZING, AND PROVIDING FEEDBACK FOR MOVEMENT IN MULTIDIMENSIONAL SPACE

Inventors: Ariel Veronica Dowling, Stanford, CA (US); Julien Favre, Stanford, CA (US); Thomas Andriacchi, Los Altos Hills, CA (US)

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

Abstract

The present invention provides systems and methods that measure and analyze a user's movement during a specific activity, then provide immediate, focused feedback as to how the user can modify the movement.
FIG. 1

100

120 MEASURE

140 PROCESSING ANALYSIS AND EVALUATION

160 DISPLAY IMMEDIATE INDIVIDUALIZED FEEDBACK

180 RECORD
FIG. 4
### FIG. 8A

<table>
<thead>
<tr>
<th>Knee Flexion Angle (°)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>9</td>
<td>88.8**</td>
<td>8.0</td>
</tr>
<tr>
<td>Follow-Up</td>
<td>0</td>
<td>105.0**</td>
<td>5.6</td>
</tr>
<tr>
<td>Change</td>
<td>-9</td>
<td>16.2</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trunk Lean (°)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>10</td>
<td>23.6**</td>
<td>8.0</td>
</tr>
<tr>
<td>Follow-Up</td>
<td>0</td>
<td>41.0**</td>
<td>3.8</td>
</tr>
<tr>
<td>Change</td>
<td>-10</td>
<td>17.4</td>
<td>8.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jump Height (cm)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td>35.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Follow-Up</td>
<td></td>
<td>35.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td>0.5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### FIG. 8B

<table>
<thead>
<tr>
<th>Thigh Coronal Angular Velocity (°/sec)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td>67.7**</td>
<td>49.7</td>
</tr>
<tr>
<td>Follow-Up</td>
<td></td>
<td>47.6**</td>
<td>40.5</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td>-20.1</td>
<td>31.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ABD Abduction Baseline (°BW*H)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td>2.0^</td>
<td>0.9</td>
</tr>
<tr>
<td>Follow-Up</td>
<td></td>
<td>1.2^</td>
<td>1.5</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td>-0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADD Abduction Baseline (°BW*H)</th>
<th>Number at Risk</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td>-1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Follow-Up</td>
<td></td>
<td>-2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td>-0.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>
SYSTEMS AND METHODS FOR MEASURING, ANALYZING, AND PROVIDING FEEDBACK FOR MOVEMENT IN MULTIDIMENSIONAL SPACE

FIELD OF THE INVENTION

[0001] This invention relates to systems and methods that measure, analyze, and provide feedback for one or more users during specific activities.

BACKGROUND OF THE INVENTION

[0002] In the following discussion, certain articles and methods will be described for background and introductory purposes. Nothing contained herein is to be construed as an “admission” of prior art. Applicant expressly reserves the right to demonstrate, where appropriate, that the articles and methods referenced herein do not constitute prior art under the applicable statutory provisions.

[0003] In recent years, increasing numbers of people of all ages have become active for all of the health benefits exercise has to offer. However, for some people these health benefits come at a price: joint injuries. The term joint injury, in the broadest sense, refers to all kinds of injuries that affect a joint. In the context of sports, some joint injuries are due to accidents; others are due to poor training practices, improper technique, lack of conditioning and the like. Even harmless repetitive movements associated with sport practices can induce injuries over the time if they are not performed correctly. These mechanisms of joint injury also apply for certain physical activities, not primarily associated with sports but associated with occupational tasks or rehabilitation that require consistent repetitions of specific body motions. Some examples of such specific body motions are walking; running; jumping; moving laterally; swinging a baseball bat; golf club or tennis racket; kicking a ball; lifting; and typing.

[0004] In the past decade, numerous systems have been proposed to simplify the measurement of human movement and to monitor users in their natural environment with little or no intervention from external personnel. However, such systems do not generally contain an independent evaluation module because their purpose is only to measure movement and not to interpret or analyze such movement without external assistance. Feedback systems have also been developed for training interventions for repetitive exercises, such as walking or running, and for use in rehabilitation. However these feedback systems typically use external measurements taken by and/or evaluated by professional personnel, such as a coach, physical therapist, exercise physiologist, and the like.

[0005] Thus, there is a need in the art for systems and methods to measure, assess, and provide feedback regarding an athlete’s or individual’s movements so as to prevent injuries and/or improve performance. The present invention addresses this need.

SUMMARY OF THE INVENTION

[0006] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description, and is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Other features, details, utilities, and advantages of the claimed subject matter will be apparent from the following written Detailed Description including those aspects illustrated in the accompanying drawings and defined in the appended claims.

[0007] The present invention provides systems and methods that measure, analyze, and evaluate a user’s movement during a specific activity to determine his or her risk for injury (traumatic or due to repetitive motion), then optionally provide focused feedback as to how the user can modify the movement. The evaluation and feedback are immediate, quantitative, and objective in nature. The feedback concentrates on modifying the user’s technique in order to reduce his or her risk for injury and, optionally, to improve his or her performance. The systems and methods of the present invention give the user individualized training as the feedback provided is based on measurements taken from the user. Further, because the evaluation criteria, movement modifications and training strategies are embedded in the system, the present invention can be used without the supervision of an expert observer or professional while delivering consistent, objective, and quality guidance. The systems and methods comprise four modules—Measurement, Processing, Feedback and Display, and Recording—that can be configured in many embodiments without significant hardware modifications to analyze a variety of different parameters associated with a host of different movements, particularly movements that permit assessment of risk for injury and training to reduce this risk.

[0008] In one embodiment, the invention provides a method for training a subject to avoid joint injuries, comprising: gathering raw data from at least one sensor attached to a subject, to an interface, or in the subject’s environment where the at least one sensor allows quantifying at least one parameter associated with a movement known to correspond to risk of joint injury; transmitting the raw data to at least one processor; evaluating the risk of injury by comparing the raw data or processed raw data to a stored model; providing feedback to the subject based on the evaluated risk of injury so the subject can alter the movement and reduce the risk of joint injury; and storing at least one of the raw data, the processed raw data, the evaluated risk data and the feedback data.

[0009] In some aspects of this embodiment, at least five sensors or more are used; and in some other aspects of this embodiment, at least ten, fifteen, twenty sensors or more are used.

[0010] In various aspects of this embodiment of the invention, the at least one sensor is a gyroscope, an accelerometer, a magnetometer, an electrode, a pressure sensor, a force sensor, a torque sensor, a force platform, a speed sensor, a goniometer, a camera, or a thermometer or various combinations of these sensors.

[0011] Various aspects of this embodiment of the invention quantify a movement performed during walking, jogging, running, jumping, throwing, swinging, kicking, swimming, rowing, squatting, lifting, pushing, climbing, cutting, blocking, skiing, snowboarding, punching, sitting, typing, cycling, or dancing.

[0012] In aspects of this embodiment of the invention, the at least one parameter is selected from joint kinematics, joint kinetics, body segment posture, body segment kinematics, body segment kinetics, and in some aspects of the invention, the at least one parameter is selected from ankle flexion, extension, rotation angle, angular velocity, angular acceleration, force, moment, or power; knee flexion, abduction, rotation angle, angular velocity, angular acceleration, force,
moment, or power; hip flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; spine flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; shoulder flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; elbow flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; wrist flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; foot position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, force, moment, or power; neck flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; shank position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; thigh position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; pelvis position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; trunk position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; upper arm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; forearm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; hand position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; head position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk. In certain aspects of the invention, the at least one parameter is selected from force, pressure, or moment between the subject and an interface or the environment. In certain aspects of the invention, the at least one parameter is selected from muscle activity. In some aspects, two, three, four, five, ten, or twenty or more of these parameters are measured.

[0017] In some aspects, the methods are used to increase a subject's performance in addition to reducing the risk of joint injuries.

[0018] In some aspects of the invention, the feedback provided is visual, and some aspects of the invention, the visual feedback is a graph, an avatar, or three-dimensional and/or any combination of these. In some aspects, the feedback provided is auditory or is tactile or haptic or a combination of any of these, or any combination of these with visual feedback configurations.

[0019] In some aspects of this embodiment of the invention, the joint injury is selected from a joint injury to a knee, elbow, wrist, ankle, hip, shoulder, or spine.

[0020] Other embodiments of the invention provide a body movement training system comprising: at least one sensor configured to measure at least one parameter associated with a movement known to correspond to risk of joint injury; transmitters associated with at least one sensor to transmit raw data related to the at least one parameter to at least one processor; at least one processor configured to receive the raw data from the transmitters, process the raw data, compare the raw data or processed raw data to a stored model, evaluate the risk of joint injury based on the comparison of the raw data or processed raw data to the stored model, and generate feedback data; a display or interface device to provide immediate feedback to the subject based on the feedback data; and a storage medium to record the raw data, the processed raw data, the evaluated data and the feedback data.

[0021] In some aspects, the feedback provided is visual, including but not limited to graphs, avatars, three-dimensional graphics and/or combinations thereof. In some aspects, the feedback provided is auditory, tactile or haptic or combinations of any of these.

[0022] In some aspects, the joint injury is a joint injury to a knee, elbow, wrist, ankle, hip, shoulder, or spine.

[0023] In some aspects, system is used to increase a subject’s performance in addition to reducing the risk of joint injuries.

[0024] Yet other embodiments and aspects of the invention are described in the Detailed Description below.
DESCRIPTION OF THE FIGURES

[0025] FIG. 1 is a simple flow chart showing the modules of the present invention.

[0026] FIG. 2 shows an exemplary experimental protocol for a testing session using the systems and methods of the invention. Vertical arrows indicate when feedback may be given to subjects in this exemplary protocol.

[0027] FIG. 3 is a table showing a standardized set of movement modifications for a training session for reducing the risk of anterior tibial ligament (ACL) injury.

[0028] FIG. 4 shows graphs of time continuous parameters and associated discrete metrics for one subject during one jump. Figures above the graphs illustrate jump sequence, and the grey box indicates stance phase. GC—Ground Contact, ED—End of Deceleration, TO—Toe Off.

[0029] FIG. 5 shows graphs of four feedback variables as measured in a testing session for one subject. For each variable, the first data point (first x) indicates mean baseline value, subsequent data points (x’s) indicate training jump values, and the last data point (circle) indicates the most recently completed training jump. Shading indicates lower risk range. For thigh coronal velocity, 0% sec was the target value and for jump height, the subject was asked to maintain the mean baseline value.

[0030] FIG. 6 shows a feedback history for a full test (baseline to follow-up) for a typical subject. For each feedback variable, the first data point (circle) indicates mean baseline value, subsequent data points (triangles) indicate training jump values, and the last data point (cross) indicates the mean follow-up value. Shading indicates lower risk range.

[0031] FIG. 7 shows the change in knee flexion angle, trunk lean, and thigh coronal angular velocity by subject from baseline to follow-up. Shading indicates lower risk range.

[0032] FIGS. 8 A and B are tables. FIG. 8 A is a table listing knee flexion angle, trunk lean, and jump height at baseline and follow-up. Number at risk indicates number of subjects outside the low risk ranges. Two stars (***) indicate significant difference between baseline and follow-up (p<0.001). FIG. 8 B is a table listing thigh coronal angular velocity and knee abduction moment at baseline and follow-up. For thigh coronal angular velocity, change was calculated as the difference between the absolute value at baseline and the absolute value at follow-up. Knee abduction moment was split into at-risk (ABD Baseline) and not-at-risk (ADD Baseline) cohorts. The at-risk cohort had a positive (abduction) peak moment at baseline while the not-at-risk cohort had a negative (adduction) peak moment at baseline. One star (*) indicates significant difference between baseline and follow-up (p<0.01), and one hat () indicates a trend to significant difference between baseline and follow-up (p<0.06).

[0033] FIG. 9 are bar graphs showing the change in knee abduction moment by subject from baseline to follow-up, split into at-risk and not-at-risk cohorts at baseline. The at-risk cohort (top) had a positive (abduction) peak moment at baseline while the not-at-risk cohort (bottom) had a negative (adduction) peak moment at baseline. Shading indicates lower risk range.

[0034] FIG. 10 shows the six phases of the pitching motion: windup (A), early cocking (B), late cocking (C), acceleration (D), deceleration (E), and follow through (F). The windup begins when the pitcher initiates his motion and ends when he removes the ball from his glove. In the early cocking stage, the stride leg extends toward the batter, the knee and hip of the pivot leg extend as well, and the body is propelled forward into the stride. The early cocking (stride) phase ends when the stride foot contacts the ground. During late cocking, the trunk rotates forward, while the shoulder achieves a position of maximal external rotation. In the acceleration phase, the shoulder is powerfully internally rotated; and, following ball release, strong deceleration forces are then applied to the shoulder as it internally rotates. When the arm reaches a position of 0° internal rotation, the deceleration phase is complete. During the less violent follow-through phase, the arm is adducted across the pitcher's body (see Park et al., Bull. Hosp. Jt. Dis. 61:1-2 (2002-2003)).

DETAILED DESCRIPTION OF THE INVENTION

[0035] The practice of the techniques described herein may employ, unless otherwise indicated, conventional techniques and descriptions of biomechanics, rehabilitation, neurobiology, physiology, electrophysiology, physical conditioning, data analysis, or signal processing, all of which are within the skill of those who practice in the art. Specific illustrations of suitable techniques can be had by reference to the Examples herein; however, other equivalent conventional procedures can, of course, also be used. Such conventional techniques and descriptions can be found in standard manuals and texts such as Winter, Biomechanics and motor control of human movement, Fourth Ed., 2009 (John Wiley & Sons); Mow et al., Basic orthopaedic biomechanics & mechano-biology, Third Ed., 2005 (Lippincott Williams & Wilkins); Kenney, et al., Physiology of Sport and Exercise, Fifth Ed., 2011 (Human Kinetics); Eston and Reilly (Eds.), Kinesiology Laboratory Manual: Anthropometry and Exercise Physiology, 2009 (Rutledge); Hamilton, et al., Kinesiology: Scientific Basis of Human Motion, 2007 (McGraw Hill); ACSM, ACSM’s Guidelines for Testing and Prescription, Eighth Ed., 2005 (Lippincott Williams and Wilkins); Heyward, Advanced Fitness Assessment and Exercise Prescription, Sixth Ed., 2010 (Human Kinetics); Baechle and Earle, Essentials of Strength Training and Conditioning, Third Ed., 2008 (Human Kinetics); Blazevich, Sports Biomechanics: The Basics: Optimizing Human Performance, 2010 (A&C Black); Hay, Biomechanics of Sports Techniques, Fourth Ed., 1993 (Benjamin Cummings); and Bartlett and Bussey, Sports Biomechanics: Reducing Injury Risk and Improving Sports Performance, 2011 (Rutledge); Fayyad et al., Advances in knowledge discovery and data mining, 1996 (MIT Press); Proakis et al., Digital signal processing, Fourth Ed. (Lavoisier), all of which are herein incorporated in their entirety by reference for all purposes.

[0036] Note that as used herein and in the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a metric for ACL injury” refers to one or more metrics for ACL injury, and reference to “administering” or “administration” includes reference to equivalent steps and methods known to those skilled in the art, and so forth.

[0037] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. All publications mentioned herein are incorporated by reference for the purpose of describing and disclosing devices, formulations and methodologies that may be used in connection with the presently described invention.

[0038] Where a range of values is provided, it is understood that each intervening value, between the upper and lower
The present invention provides systems and methods that measure, analyze, and evaluate a user’s movement during a specific activity to assess his risk for injury, including joint injuries, and optionally provide focused and immediate feedback as to how the user can modify the movement. The evaluation and feedback are both quantitative and objective. The feedback concentrates on modifying the user’s technique in order to reduce his or her risk for injury, as well as optionally improve his or her performance. “Immediate” means providing feedback where the processing system responds as rapidly as necessary to the subject’s movement; in some embodiments (such as described in Examples 2 and 4 herein), feedback is provided in real-time while the subject is performing the movement(s), and in other embodiments (such as Examples 1 and 3 herein), the feedback is provided directly following the subject’s performance of the movement. The systems and methods of the present invention give the user individualized training as the feedback provided is based on measurements of the individual. Furthermore, because the evaluation criteria, movement modifications and training strategies are embedded in the system, the present invention can be used without the supervision of an expert observer or professional while delivering consistent and quality guidance. The systems and methods generally comprise four modules—Measurement, Processing, Feedback and Display, and Recording (see FIG. 1)—that typically can be configured without significant hardware modifications to analyze a variety of different movements, including movements that permit assessment or training relative to risk for injury, performance or both.

The movements that can be measured and evaluated by the present invention are almost endless and include a broad range of sports activities, such as throwing (baseball, football, tennis serves), jumping (basketball, volleyball), sprinting (track, soccer, football), and weight lifting (squatting, free weights, and the like). Furthermore, the invention also may assess rehabilitation movements as well as movements associated with repetitive occupational tasks such as lifting and other tasks associated with ergonomic evaluations. Conditions associated with aging, such as risk of falls or diminution of balance, as well as assessment of compensatory movements, also may be monitored by the systems and methods of the invention. The critical problem addressed by the present invention is how to provide individualized measurement, analysis, evaluation, and feedback on movement technique any time and virtually anywhere without external assistance from a third party such as a coach, physical therapist or other professional.

[0042] The methods and systems of the present invention can be used to train individuals to move in a way that is less likely to result in injury, for example, joint injuries, bone fatigue fractures, muscle strains and the like.

[0043] One preferred application of the systems and methods of the present invention is to reduce the risk of joint injuries. The joints of the human body are subject to many types of injuries, including sprains (overstretching of the ligaments that hold the bones of a joint together), strains (overstretching the tendons), and tears or ruptures of the ligaments, tendons, articular cartilages, or intervertebral discs. In particular, the knee joint is one of the most commonly injured joints due to its complex structure and the high loads that it sustains. Injuries to the knee include sprains, tears or rupture of the anterior or posterior cruciate ligaments, patellar tendinitis, meniscal tears, and other knee strains. Other joints prone to injury during sports or occupational activities include the elbow and wrist (dislocations, sprains, strains), the ankle (Achilles tendinitis, sprains, and strains), the hip (dislocation), the shoulder (dislocations, strains, sprains, rotator cuff tears, separated shoulder), and the spine (disc herniation). Avoiding such injuries not only prevents the direct injury, but prevents long-term deterioration and degeneration of the joint. The systems and methods of the present invention can be used to measure, analyze, and evaluate an individual’s unique movement, and then optionally provide focused feedback as to how the individual can alter his or her movement to reduce risk of injury.

[0044] Another preferred application of the systems and methods of the present invention is the use of the invention to improve or optimize performance. For example, during sports where an athlete must move quickly with high accuracy, it is of interest to be able to measure the timing, accuracy, and consistency of the phases of the athlete’s movement, for example: swinging a golf club or tennis racket, passing a football, serving a volleyball or tennis ball, jumping to spike a volleyball or shoot a basket, performing a turn in swimming, and other such movements. Consistent timing and body positioning are cornerstones for repeatability of performance, and muscle memory is key to consistent timing and body positioning. Through training, conditioning, analysis, and feedback, an athlete’s variations in technique can be reduced, and a proper movement ingrained. Additionally, such training does not only apply to athletes, but can be used to train non-athletes, such as individuals going through rehabilitation after a stroke or other physical challenges, or individuals who perform repetitive occupational tasks.

[0045] In some embodiments, the device focuses only on evaluating the risk of injury or the performance and does not provide any feedback to the subject on how to alter the movement. In these embodiments, the primary function of the device is to provide only an assessment of the subject’s movements. This assessment may be used to determine if the subject is at risk for a specific injury, to identify subjects that need to be enrolled in an injury prevention program, or to monitor changes in a subject’s risk of injury over a period of time. These embodiments also can be used to determine if the performance of the subject is improving, to determine if the risk of injury is changing as the performance changes, or to track a subject’s performance as they progress through a training program. In these cases, the invention will serve as a
quantitative assessment tool that may provide valuable information to the subject as well as to trained professionals assisting the subject. The assessment provided may then be used to determine a future plan for the subject, alter the current plan, or determine if the subject needs additional training for injury prevention or performance enhancement.

[0046] FIG. 1 is a simple flow chart showing the Modules of the methods 100 of the present invention. In its simplest form, the systems and methods of the present invention provide modules to measure 120 the signal from sensors during one or more movements made by an individual (Measurement Module); process the data 140 acquired by the Measurement Module to obtain continuous parameters and discrete metrics that describe the movement quantitatively, evaluate the risk or performance, and provide data to control the feedback associated with the one or more movements (Processing Module); provide immediate, complex, and individualized feedback and/or simply display the results of the risk or performance evaluation 160 to the individual (Feedback and Display Module); and record 180 the measurement, evaluation, feedback and other data associated with the methods (Recording Module). Each Module is described in more detail below.

Measurement

[0047] The Measurement Module of the present invention measures the signal from sensors during one or more movements made by an individual. For example, movements that may be evaluated include but are not limited to walking; jogging; running; jumping; movement of an arm when swinging a tennis racket, golf club or throwing a baseball, football or serving a volleyball; kicking a ball; leg and arm movements while swimming; rowing; squatting; lifting; pushing; climbing; cutting; blocking; body movements during skiing or snowboarding; shooting a basketball; aiming a gun; martial arts punches and kicks; work related movements such as typing while sitting or moving heavy objects; and the like. Parameters associated with the movements generally involve joint angles, body segment posture, body segment kinematics and kinetics, and the like, including but not limited to: ankle, knee, hip, spine, shoulder, elbow, wrist, and neck flexion, abduction, and internal rotation angle, angular velocity, and angular acceleration; foot, Shank, thigh, pelvis, trunk, upper arm, forearm, hand, and head position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration and angular jerk; muscle activation; and the associated kinetic parameters. The Measurement Module may also involve sensors to measure metrics like stride length, step length, cadence, progression line, toe-out angle, jump height and length, and the like.

[0048] Devices used in measuring the various parameters of movement include sensors placed on desired parts of the body segments, in the environment, on the floor, or placed on different interfaces or objects. These sensors include but are not limited to gyroscopes to measure angular velocity; accelerometers to measure inclination or linear acceleration; magnetometers to measure magnetic field strength or direction; electrodes to measure changes in electrical potential, muscle activation, or heart rate; pressure, force, or torque sensors to measure kinetic interaction between body parts and interfaces; cameras coupled with or without markers to measure position of body segments or objects; force platform systems to measure ground reaction forces and moments; goniometers to measure joint angles; speed sensors to measure speed; and temperature sensors to measure body parts or ambient heat.

These sensors are connected to one processor or to a network of processors that acquires the movement data during the testing session by sampling and storing the signal from the sensors at predefined sampling frequency. The signals may be processed by a processor or network of processors to provide feedback to the user.

Processing: Analysis and Evaluation

[0049] In the Processing (Analysis and Evaluation) Module, data acquired by the sensors and stored in a memory during the subject’s movement (Measurement Module) is processed to obtain specific time continuous descriptive parameters (for example: knee angles, position of the head, medial-lateral velocity of the subject’s center of mass, etc.). These parameters are then extracted from these parameters to quantify the movement (for example: maximum knee flexion during stance, highest position of the head, mean value of the medial-lateral velocity of the subject’s center of mass, etc.). This Module also uses a “comparison model” to evaluate the risk for injury and provide data on how the user can alter his or her technique to reduce the risk for injury. The comparison model consists of comparing the subject’s actual movement (described by a set of discrete metrics) with a target (reference) movement execution. Analysis of the data acquired in the Measurement Module of the invention typically involves both standard and custom algorithms. These algorithms include but are not limited to altering the measurement units; calibrating the signals to account for the location of the sensors on the body segments, on the objects, or in the environment; smoothing or filtering the signals; analyzing and combining the signals to obtain specific descriptive parameters; extracting discrete metrics from the descriptive parameters; comparing the subject’s movement (described by a set of discrete metrics) with a target movement using a comparison model to evaluate the risk of injury and, optionally, the performance, and to provide data on how the user can improve his or her technique; and finally making the continuous parameters, discrete metrics, results of the risk or performance evaluation, and the data for the feedback available to the Feedback and Display Module.

[0050] The first step of the analysis is to conduct calibration routines for each sensor to obtain signals in the proper units. The units of the signals from the sensors are converted from the measured units (like volt) to the desired measurement units (like degree per second, or g-force) using predefined calibration equations. Then, the signals are modified based on the individual placement of the sensors and conditions of the testing session. All calibration procedures are customized to the specific types of sensors being used as well as the location of the sensors on the body segments, on the objects, or in the testing environment. For example, calibration routines for an accelerometer attached to a body segment identify the position and orientation of the sensors relative to the segment. Additionally, in some cases, the sensors are adjusted based on the initial conditions of the testing session (initial position, orientation, temperature, etc.).

[0051] The data may be filtered or smoothed using either standard signal processing filters (Butterworth filters, Gaussian filters, etc.) or custom designed filters specific to the application.

[0052] Once the data is in the proper units and adjusted, a customized analysis of the movement is completed, which depends on the type of sensors used and the movement analyzed. In general, the signals are processed to obtain specific time continuous descriptive parameters (for example: knee angles, position of the head, medial-lateral velocity of the
subject’s center of mass, etc.), critical temporal features of the movement are then identified (for example, the start and stop times of the movement, and any distinctive time points like take-off, landing, ball catching and release, etc.), and discrete metrics are determined either as values of the descriptive parameters at those critical time points (for example: knee flexion at take-off, etc.) or statistical reduction of the parameters between time points (for example, the mean value of the medial-lateral velocity of the subject’s center of mass, etc.). If a desired parameter is not measured directly, the data from the sensors is manipulated to produce the desired parameter; for example, position may be the desired descriptive parameter but velocity is actually measured, therefore velocity is integrated to calculate position. The sensor data may also be combined to reduce the error of measurement using methods such as Kalman filtering; for example, position data calculated from velocity may be enhanced using occasional position data to correct for drift in the non-ideal velocity sensor. [0053] Finally, the discrete metrics are used to compare the subject’s movement to a target execution of the movement using a comparison model. The model typically is embedded in the system and has been determined prior to the measurement at hand. The model varies depending on the movement measured as well as the desired goal of the evaluation and possible feedback (injury prevention, performance evaluation). The model may consist of a comparison with discrete target metrics or may consist of a data manipulation algorithm, such as a neural network, a principal component analysis, or the like that perform a comparison considering all the discrete metrics simultaneously. Subject specific metrics may be included in the model, like the subject’s age, height, weight, dominant leg/hand, ethnicity, and the like. The model may also include reference data, which may be either ideal data generated from computational methods or actual data collected from a variety of exemplar subjects prior to the measurement at hand. The model may be adjusted based on the specific circumstances of the subject, the movement to be measured, and the desired goal of the evaluation or feedback. [0054] The outputs of the comparison model are an evaluation of the risk of injury; for example, in the form of a score or of similarities and differences compared to the target execution of the movement using a set of the discrete metrics or other evaluation variables. The model may also provide additional outputs that will be used to control the feedback and indicate how the user can modify his or her technique to be less at risk for injury, or outputs describing the movement or the performance. Finally, the Processing Module transmits the time continuous parameters, temporal features, discrete metrics and the outputs of the comparison model to the Feedback and Display Module which will use the data to control the feedback provided to the user or display the results of the evaluation. Feedback and Display [0055] The type and quantity of feedback provided depends on the specific embodiment of the invention. The feedback is based on the data transmitted by the Processing (analysis and evaluation) Module. Feedback may be provided to the subject in any number of ways. Various graphical displays may be used to provide feedback. For example, feedback may be provided by displaying the outputs of the comparison model in chart or graph form, as shown in FIGS. 4 and 5, on a monitor or other display. The charts or graphs may display not only the most recent variables, but a series of variables taken over time (as shown in FIG. 5), as well as risk, target, desired and/or optimal performance ranges for those variables, and the like. Alternatively or in addition, the graphical display may include images of the subject (or an avatar) performing the movement, with superimposed visual indicators showing optimal movement accomplishment. In some embodiments, the display may use perspective techniques to display a three-dimensional animation such that body movements can be seen from different points of view in a three-dimensional space. Furthermore, the graphical display may include videos of other subjects performing ideal or non-ideal jumps with explanations and/or comparisons to the current subject’s movement. In addition, information such as text or a cartoon might be provided. The graphical display may be on a computer monitor, a TV, a smartphone, provided by a projector, or other type of display platform. Similar visual methods to the methods presented in this paragraph are used to communicate the results of the risk or performance evaluation to the user. [0056] In addition to using graphical displays, feedback may also be provided to the subject by way of audio signals, such as bells, beeps, buzzers, chimes, alarms, a synthetic voice giving instructions, or other suitable sounds. In some embodiments, the sounds audible to the subject can be descriptive: one sound (e.g., a clicking sound, a buzz, a beep of one tonality) can indicate that a movement has been performed inappropriately; another sound (e.g., a swoosh sound, a pleasant chord, or a beep of a different tonality) can indicate that the movement has been performed appropriately. In some embodiments, the pitch, intensity, and/or frequency of the sound can change to provide information about how much the subject’s movement and/or position varies from a certain value or range of values or to provide other information to the subject. Audio feedback may be provided from feedback devices located on the subject’s body or separated from the body. [0057] Other sensory cues can be used as an alternative to or in addition to graphical or auditory signals. For example, feedback mechanisms may comprise haptic devices that provide vibrations, forces, or pressure that can be detected by the subject. The feedback may include one or more vibration devices placed on the body of the subject that can indicate if the movement has been performed appropriately; the type and strength of the vibration can also be used to provide information to the subject. Alternatively or additionally, this feedback might include resistive or constructive forces to the subject’s body to indicate the desired ideal movements or to prevent the subject from moving in a non-ideal manner. These resistive or constructive forces may be produced by a variety of actuators, and may be controlled by a variety of control mechanisms. The feedback may also be pressure actuators that apply pressure to the body to indicate how the subject should conduct the movement. These pressure actuators may also vary in location and intensity based on the desired feedback necessary for the subject. [0058] In some embodiments, the visual, audio, or other types of feedback can also be used prescriptively. For example, a series of sounds can be emitted that correspond to the proper rhythm of the movement, and the subject can match the movement to the cadence of the sounds. Visual and haptic indicators can be prescriptive or descriptive as well. Recording [0059] The data produced by the systems and methods of the present invention can be recorded, stored, and retrieved
using hardware and software well known to those skilled in
the art. Generally, the systems of the present invention com-
prise a storage device such as a disk drive, RAM, or memory
card. The storage device records the data acquired and ana-
lyzed by the system and also provides access to the data.

EXAMPLES

[0060] The following examples are put forth so as to pro-
vide those of ordinary skill in the art with a complete disclo-
sure and description of how to make and use the present
invention, and are not intended to limit the scope of what
the inventors regard as their invention, nor are they intended
to represent or imply that the experiments below are all of or
the only experiments performed. It will be appreciated by
persons skilled in the art that numerous variations and/or modi-
fications may be made to the invention as shown in the spe-
cific embodiments without departing from the spirit or scope
of the invention as broadly described. The present embodi-
ments are, therefore, to be considered in all respects as illus-
trative and not restrictive. Efforts have been made to ensure
accuracy with respect to numbers used but some experimental
errors and deviations should be accounted for.

Example 1

Anterior Cruciate Ligament (ACL) Injury Prevention

[0061] Extensive sections of the following example are
excerpted from Dowling AV, Favre J, Andriacchi TP. Entitled
“Inertial sensor-based feedback can reduce key risk metrics
for ACL injury during jump landings.” The final definitive
version of this paper is in press to be published in the Ameri-
кан Journal of Sports Medicine, by SAGE Publications Inc.,
all rights reserved.

[0062] The anterior cruciate ligament (ACL) is the most
commonly injured ligament of the knee, and loss of this
ligament often leads to premature degenerative arthritis of
the knee. As such, researchers have developed intervention
programs that can successfully decrease the incidence of ACL
injury. These preventive programs are generally six to eight
weeks in duration and require two to three training sessions
per week that are focused on altering lower extremity biome-
chanics. Most of these training sessions occur during team
practices because the participants cannot perform the in-
tervention training independently. As a result, compliance
rates can be as low as 28% (see, Myklebust, et al., Clin J. Sport
Med, 13(2):71-78 (2003)). Further, either an instructor or a
physical therapist must be present to coach the participants
in order to ensure that they are properly performing the training
intervention. Coaching generally consists of verbal instruc-
tions based on visual observations. Therefore, such coaching
is not quantitative in nature and can vary depending on
the skill of the observer. The independent and quantitative feed-
back systems and methods of the present invention greatly
improve these intervention programs by allowing the subjects
to conduct the training sessions on their own while receiving
consistent, objective instructions based on measurements
from the subject.

[0063] Many successful intervention programs emphasize
proper jump landing technique because landing from a jump
is one of the primary non-contact ACL injury mechanisms.
Specific kinematic and kinetic risk factors, such as a small
knee flexion angle, small trunk flexion angle, and large knee
abduction moment, have been shown to increase the risk for
ACL injury during a jump landing. Consequently, these risk
factors have been the focus of several intervention studies;
however, measuring these parameters using prior art methods
and systems required a complex setup (e.g., gait laboratory)
as well as a substantial amount of time to prepare the subject
and process the data. Thus, in general, these parameters are
not rigorously measured outside of a research environment
and are instead estimated through visual observation.

[0064] The study described herein provided immediate
visual feedback based on measurements of parameters (knee
flexion angle, trunk lean, and thigh coronal angular velocity)
using a simple inertial sensor-based system to modify specific
ACL injury risk parameters (knee flexion angle, trunk lean,
knee abduction moment) during jump landing.

Protocol

[0065] Subjects

[0066] Seventeen subjects (7 male and 10 female) with an
average age of 27.5±2.9 years and BMI of 22.8±2.3 were
selected for this study. All were regular participants in sports
involving jumping maneuvers at the recreational level. Sub-
jects with previous lower limb musculoskeletal injuries
requiring surgery or any current symptoms of pain or injury
were excluded.

[0067] Movement

[0068] The movement considered in this study was a bilateral
support drop jump maneuver in a gait laboratory. For this
task, each subject dropped off a 36 cm box, landed with both
feet on the ground, and then immediately performed a maxi-
imum height vertical jump. The landing directly after the drop
from the box was used for the analysis (FIG 4). The jump was
considered acceptable if the subject dropped off the box with
both feet at the same time and fully impacted a force plate
embedded in the ground with their right-side foot.

[0069] Experimental Design

[0070] The experimental protocol consisted of seven parts
(see FIG. 2). During the preparation part, the embodiment of
the invention and reflective markers for an optoelectronic
system (Qualisys Medical, Gothenburg, SE) were placed on
the subjects. The subjects then performed a short warm-up
consisting of light jogging and/or squatting. When the sub-
jects felt ready, calibration procedures were performed for the
feedback and optoelectronic systems. After that, the jumping
task was explained to the subjects, and they were allowed to
practice until they felt confident with the task. At this point,
the subjects conducted a baseline testing session consisting of
two drop jumps. For the baseline session, no landing instruc-
tions were provided and the subjects were not aware of what
the feedback variables would be. Following the baseline test-
ing, the subjects completed a training session of 15 to 20
jumps within approximately 30 minutes where they received
feedback on their jumping technique. Immediately after the
training session, the subjects conducted a follow-up session
also consisting of three drop jumps to assess the change of
injury risk after training. For the follow-up testing, the sub-
jects were asked to maintain the jumping technique that they
learned during the training session. The subjects also had the
opportunity to repeat a jump during this session if they felt
that they did not successfully accomplish the movement
modification.

[0071] Once the baseline testing was complete, the results
of the risk evaluation (based on the three baseline jumps) were
shown to the subjects. The principle of the feedback and the
feedback variables were then verbally explained to the sub-
ject using a standardized speech. The subjects were told they would have between 15 and 20 jumps to incorporate the modifications into their jumping technique. When the subjects achieved a jumping technique that optimized all the feedback variables to the best of their ability, or when they reached 20 training jumps, they were asked to maintain that technique for the follow-up trials.

EMBODIMENT OF THE INVENTION

[0072] Measurement Module
[0073] In this embodiment of the invention, three small inertial measurement units (Physilog®, BioAGM, CH) affixed on the chest, thigh, and shank segments respectively were used to measure the movement. These units were connected to a computer that recorded the signal from the inertial sensors at 240 Hz during the jump task.

[0074] Processing Module
[0075] Using custom software, the raw signals coming from the inertial sensors were adjusted to be insensitive to the actual placement of the sensors on the body segment (functional calibration). Then the knee flexion angle, trunk lean, and coronal thigh angular velocity continuous descriptive parameters (FIG. 4) were calculated immediately after the subject completed the jump trial based on the signals from the inertial sensors. One characteristic discrete metric previously identified as being associated with ACL injury was then extracted from each kinematic time series (FIG. 4). For the knee flexion angle and trunk lean, the maximum values achieved during stance were chosen because they have been suggested as risk factors for ACL injury and are common components of intervention programs. For the thigh coronal angular velocity, the first maximum (inward) peak during stance was selected because it is correlated to the knee abduction moment, which is a strong predictor of ACL injury risk. Additionally, jump height was included as another metric to monitor the overall performance of the jump. The technical details of this system, as well as its validation for drop jump analysis, have been previously described (see, e.g., Dowling, et al., J. Biomech Eng., 133(7):071008; Dowling, et al., J. Biomech., in review, both of which are incorporated herein in their entirety for all purposes).

[0076] The comparison model consisted of comparing the maximum knee flexion, maximum trunk lean and peak thigh angular velocity metrics with predetermined target values. Based on the literature, a direction associated with a higher risk for injury was determined for the three metrics (i.e., knee extension, backward trunk lean and inward thigh coronal angular velocity). The actual target values for the evaluation were determined based on previous research on healthy subjects conducting drop jumps that used the same inertial sensor-based system (see, e.g., Dowling, et al., J. Biomech Eng., 133(7):071008). Knee flexion angle and trunk lean have been widely documented in the context of ACL injury; therefore “lower risk” ranges were defined for these two parameters and the subjects were considered as being at greater risk for injury if their metrics were outside these ranges. The lower risk ranges, [88°; 120°] for the knee flexion angle and [25°; 60°] for the trunk lean, corresponded to the upper half [median; maximum] of the data previously collected with healthy subjects. No target range was defined for the thigh coronal angular velocity because a risk threshold has never been reported for this parameter nor has it been used in an intervention program. Instead, the level of risk for this metric was determined based on its difference compared to a neutral landing (i.e., with the first peak of the thigh coronal angular velocity equal to 0°/sec); the greater the difference, the greater the risk.

[0077] Finally, the Processing module transmitted the outputs of the risk analysis as well as the jump height to the Feedback and Display module.

Feedback and Display Module

[0078] For this embodiment, the feedback consisted of a projector displaying graphs showing time series (one data point per jump) of the feedback variables as well as target values (FIG. 5). After each jump, the display was immediately updated to add the results of the latest jump to the subject’s training history. Subjects were instructed to modify their mechanics in order to be to be within those targets and they were provided with a standardized set of movement modifications for each variable that would reduce their risk of injury (FIG. 3). The feedback variables consisted of the three kinematic metrics used for the risk evaluation (maximum knee flexion angle, maximum trunk lean, and peak coronal thigh angular velocity) plus jump height. The target values for the maximum knee flexion and maximum trunk lean were the lower risk ranges previously described, the target value for the peak thigh angular velocity was the neutral landing, and the target for the jump height was the values of the jumps height during the baseline session (i.e., the athlete was asked to maintain his or her jump height). For the knee flexion angle and trunk lean, the lower risk range was shaded. This visual feedback is illustrated in FIG. 5. The subjects were instructed to modify their landing mechanics in order, starting with the knee flexion angle (if necessary), then the trunk lean (if necessary), and finally the thigh coronal angular velocity (if necessary). Regarding the jump height, the subjects were instructed to maintain their baseline height during all the jumping trials. In this experimental study, examiners assisted the subjects during the training by repeating the standardized set of movement modifications as many times as requested by the subjects. Also, if the examiners observed that the subjects were demonstrating a consistent landing technique and were not progressing anymore, the examiners would suggest to the subjects that they could move on to the next feedback parameter. However, the systems and methods of the invention can be configured to provide such information to the subjects in, e.g., the Feedback Module.

[0079] Recording Module

[0080] For this embodiment of the invention, the raw and adjusted signals from the sensors, the time continuous parameters, the discrete metrics, the feedback variables, and the feedback targets were stored in a memory after each jumping trial.

Auxiliary Evaluation System

[0081] The system of the present invention analyzed the first peak of the thigh coronal angular velocity because this parameter has been shown to be associated with the peak knee abduction moment during a drop jump landing, which is a strong predictor of ACL injury risk. However, the thigh coronal angular velocity has never been directly related to ACL injury nor has the effect of a modification of this parameter on the knee abduction moment been investigated. Therefore, an auxiliary system was used to measure the knee kinetics in order to determine whether the intervention decreased the risk of injury in terms of the knee abduction moment. This
auxiliary system consisted of an optoelectronic motion capture system (Qualisys Medical, Gothenburg, SE) with ten infrared cameras collecting at 120 Hz and one force plate (Bertec, Columbus, Ohio) collecting at 1200 Hz. The point cloud technique was used to track the orientation of the foot, shank, and thigh frames (see Andrieu et al., J. Biomech. Eng., 120(6):743–49 (1998)), and the knee abduction moment was calculated using an inverse dynamic approach. The subjects demonstrated two landing strategies for the knee abduction moment: some subjects landed with primarily an abduction moment while others landed with primarily an adduction moment. To preserve these strategies, the average moment during the deceleration phase of the landing was calculated. If this average was positive (mainly in abduction), then the maximum value (abduction peak) was reported; otherwise the minimum value (adduction peak) was reported. To allow for comparison between subjects, the knee abduction moment was normalized to percent bodyweight and height (% BW*Ht).

Statistical Analysis

For each of the five metrics considered in this study (knee flexion angle, trunk lean, thigh coronal angular velocity, knee abduction moment, and jump height), during both the baseline and the follow-up sessions the values from the three jumps were averaged in order to have one mean value per subject per session. Paired Student t-tests (baseline vs. follow-up) were used to evaluate the effects of the training. All statistical tests were performed in MATLAB version R2016b (The Mathworks, Natick, Mass.) and the significance level was set a priori to 0.05.

Results

Within a 20 jump training session, all of the subjects were able to respond to the feedback from the inertial sensor-based system in terms of the knee flexion angle and the trunk lean, and most of the subjects also were able to change the amplitude of their thigh coronal angular velocity. The feedback history for a full test (baseline to follow-up) is shown for a typical subject in Fig. 6. In terms of the maximum knee flexion angle, at baseline some subjects were outside the lower risk range, and at follow-up all subjects were inside the pre-defined range (see FIGS. 7 and 8A). All but one subject increased their knee flexion angle during the training (average change: 16.2°, p<0.001), and the one subject that did not had a relatively high baseline value (104°). The results were similar for the maximum trunk lean. At baseline, some subjects were outside the lower risk range, and at follow-up all subjects were inside the range (see FIGS. 7 and 8A). All 17 subjects increased their trunk lean during the training (average change: 17.4°, p<0.001). In terms of thigh coronal angular velocity, at baseline 16 subjects had a positive value (indicating an inward movement of the thigh after initial contact) and one subject had a negative value (indicating an outward movement of the thigh after initial contact). After training, 13 subjects landed with a more neutral thigh coronal angular velocity, and 4 subjects were not able to complete the third modification. Overall, the subjects decreased the absolute amplitude of the first peak of the thigh coronal angular velocity by 20.1°/sec (p<0.01) (see FIGS. 7 and 8B). The subjects also maintained the same jump height from baseline to follow-up (p=0.6), and the average change in jump height was 0.5 cm.

Regarding the peak knee abduction moment, the average change for all the subjects was -0.5% BW*Ht (p<0.001). For further analysis, the subjects were split into two cohorts based on their baseline values because previous work has shown that only an abduction moment increases the risk of ACL injury. At baseline, 8 subjects had an abduction (positive) moment and were classified as “at-risk”, whereas 9 subjects had an adduction (negative) moment and were classified as “not-at-risk” (FIG. 9). For the at-risk cohort, 6 subjects had decreased their knee abduction moment at follow-up (-1.2% BW*Ht) while 2 had increased their knee abduction moment (0.4% BW*Ht). For the entire at-risk cohort, the average change was -0.8 BW*Ht (trend to significance: p=0.06) (see FIGS. 8B and 9). Moreover, two of the subjects in the baseline at-risk cohort had an abduction (not-at-risk) moment after the training. None of the subjects in the baseline not-at-risk cohort had an abduction (at-risk) moment at follow-up, and the average change for this cohort was not statistically significant (FIG. 9).

The results from this study show that the subjects could effectively respond to the feedback from the sensor-based system of the present invention in a single training session of up to 20 training jumps while maintaining the same jump height. The subjects were able to positively modify their jumping technique in terms of three key risk metrics for ACL injury based on the quantitative feedback from the system combined with a set of instructions. All of the subjects were able to maintain or to modify their knee flexion angle and trunk lean to be within the lower risk ranges after training. For the thigh coronal angular velocity, 13 subjects (77% of the cohort) were able to modify their jumping technique in order to land with more neutral velocity, suggesting that this parameter was more difficult to alter; however, it is important to note that the subjects were instructed to modify their landing mechanics one parameter at a time and that the thigh coronal angular velocity was the final parameter.

At follow-up, the subjects significantly reduced key risk metrics for ACL injury in terms of the kinematic risk factors. After training, the subjects increased both their maximum knee flexion angle and their maximum trunk lean during stance. The 16.2° increase obtained for the knee flexion angle is comparable to previous intervention programs consisting of a single training session reported in Mizner et al., J. Orthop. Sports Phys. Ther., 38(6):353-61 (2008), where a change of 11.3° was observed for female athletes instructed to increase their knee flexion angle during a drop jump landing. Another study by Onate that investigated different combinations of feedback during a vertical jumping task reported changes in knee flexion angle between 27° and 40° (Onate et al., Am. J. Sports Med., 33(6):831-42 (2005)). Although no study has directly reported the change in trunk lean after an intervention, the 17.4° increase observed in this study agrees with the change reported by Blackburn et al. (Clin. Biomech., 23(3): 313-19 (2008)) for trunk flexion angle during a controlled drop jump landing task. Furthermore, it is important to note that in this study the amplitude of change for each kinematic parameter was driven by the lower risk range; it is assumed that with enough training, any subject could land with an exact amplitude of knee flexion angle and trunk lean.

The decrease in the knee abduction moment between baseline and follow-up also showed that the feedback system successfully guided the subjects to decrease key risk metrics for ACL injury during the training. The average decrease of 0.8% BW*Ht for the at-risk cohort is comparable
to the results from previous intervention programs. Mizner et al. (J. Ortho. Sports Phys. Ther., 38(6)353-61 (2008)) reported a 0.65% BW*Ht reduction in the knee abduction moment for female athletes instructed to land softly and avoid knee valgus during a drop jump landing. In another study, female athletes considered at higher risk for ACL injury displayed a decrease of 0.5% BW*Ht during a drop jump landing after 7 week neuromuscular training program (see Myer, et al., BMC Musculoskelet. Disord., 8:39 (2007)).

In this study only three variables were used for the feedback because it was anticipated that the subjects would not be able to modify more than three variables during a single training session. However, there are many other known ACL injury risk factors that could be included in the feedback in order to improve the intervention without modifying the hardware or the data collection procedure (Measurement Module).

Example 2

Perfecting Squatting Form

The squat (and the related weighted squat) is one of the most frequently used exercises in the field of strength and conditioning. It is a core exercise in many training regimens because it is biomechanically and neuromuscularly similar to a wide range of athletic movements. It is also relevant to non-athletes because it trains multiple muscle groups in a single maneuver, similar to common activities of daily living like lifting packages and picking up children. Squats have also been used to strengthen lower-body muscles during rehabilitation after a joint injury (see Schoenfeld, J. Strength. Cond. Res., 24:12 (2010)).

Injuries related to the squat exercise are minimal when participants perform the exercise correctly, with proper technique and appropriate weight. However, poor squatting technique can lead to serious injury, especially during a weighted squat with heavy weights. These injuries include muscle and ligament strains, and spine maladies such as ruptured intervertebral discs, spondylosis, and spondylolisthesis. Therefore, it is critical that athletes and non-athletes training with the squat exercise use proper technique to minimize the risk of injury. The present invention can be used to train athletes and non-athletes in ideal squatting technique in order to prevent injuries related to poor technique as well as to improve performance and increase strength.

Ideal squatting technique is defined by a variety of joint kinematic metrics during the exercise, all of which can be measured by the current invention. Starting from the distal point of the body, it is important that the heels remain flat on the floor during the entire squatting exercise, as forces in the ACL are significantly increased when squatting with elevated heels during both ascent and descent (Toutouni et al., Clin. Biomech. 15 (2000)). A dorsiflexion angle in the ankle of approximately 40° is necessary to keep the heels on the floor. Furthermore, the ideal placement of the feet is shoulder-width apart, with a toe-out angle of approximately 30° (see Rippe et al., Starting Strength. ed. 2 (2007)). In terms of the knee, the ideal position at the bottom of the squat is a neutral knee (parallel with the feet) with no discernable knee abduction angle, and the thighs will be parallel with the floor with the hip joint below the patellar femoral joint. Further, the knee should extend only slightly beyond the toes, and forward knee translation should be minimized. The trunk lean angle should be approximately 45° from the horizontal at the bottom of the squat, and the torso should remain flat and rigid. In terms of speed of the maneuver, the entire movement should be conducted at a relatively slow cadence (2 to 3 seconds eccentric tempo) to prevent injury, and the hips and torso should descend and rise at the same speed (see Rippe et al., supra).

The present invention can be used to monitor and provide immediate feedback to a subject about kinematic parameters during the execution of a squatting exercise. For this embodiment, the Measurement Module consists of inertial measurement units containing accelerometers and gyroscopes placed on the subject’s foot, shank, thigh, and two on the torso (lower back and sternum). The Processing Module includes calibration routines (as described in Example 1) to identify the locations of the sensors on the body and to align the sensors in relation to one another and to the global reference frame. The initial starting position of the body is measured to determine the reference/neural position for that subject. The gyroscope and accelerometer measurements are combined together (using the method described in Example 1) to measure the kinematic time continuous parameters describing the movement of the body segments during the squat (foot progression angle, dorsiflexion angle, shank angle with the floor to determine knee position relative to the foot, knee flexion and valgus angles, trunk lean). The difference in the stationary accelerometer measurements from the calibration position to the final position is used to measure the subject’s stance width and to determine whether the thigh is parallel with the floor. The difference in measurements between the two torso sensors determines if the trunk is rigid and straight. The gyroscopes in the inertial measurement units measure the speed of the movement for each segment by measuring the segment angular velocity (similar to the previous Example).

Temporal features and discrete metrics are calculated during the execution of the movement, and a comparison model, similar to the one presented in the previous Example, based on target values for a set of discrete metrics is used to evaluate the risk for injury and to produce the variables to control the feedback.

Due to the slow execution of this activity, the Feedback and Display Module consists of true real-time feedback on body positioning. Instead of waiting until the subject has completed the movement (like in the previous Example), the subject receives feedback during the movement while he or she can still adjust how he or she is completing the exercise. Real-time feedback provided during the performance of the movement is especially beneficial for a squat exercise because most of the success of the exercise depends on the subject reaching target values. For example, the squat is considered to have been executed more successfully if the subject manages to increase his or her ankle, knee, and hip flexion angles until his or her thighs are parallel with the ground. So for this parameter (thigh angle), the feedback provided may be a combination of a vibration device and auditory device. As the subject nears the ideal position, the vibration device could provide progressively stronger feedback to the subject indicating that they are approaching the proper position; once they reach the position, the auditory device could provide an auditory cue indicating that the proper position has been reached. In this way, the subject can adjust their movements based on the feedback while the exercise is being executed in order to properly conduct the movement. Furthermore, feedback may be given if the subject goes beyond the ideal range; for example, if the subject exceeds the desired trunk lean
angle, a different auditory sound could indicate that they are outside of the ideal range and should correct their trunk positioning. Therefore, a combination of vibration and auditory feedback on the various measured parameters may indicate to the subjects during execution of the squat exercise maneuver that the proper positioning for the movement is reached. Furthermore, the feedback may be set to focus on one or two critical parameters, and additional parameters may be added so that the subject is not overloaded initially and is allowed to master the technique in incremental steps (again similar to Example 1). Overall, teaching a subject the proper technique for a squat exercise is yet another embodiment of the systems and methods of the present invention and how they may be used for real-time measurement, analysis, and feedback in order to prevent injuries and improve performance.

[0095] For the Recording Module of this embodiment of the invention, the raw and adjusted signals from the sensors, the time continuous parameters, the discrete metrics, the feedback variables, and the feedback targets are stored in a memory after each squat.

Example 3

Optimizing Baseball Throwing Mechanics

[0096] Throwing a baseball is a coordinated motion that starts in the toes and ends in the fingertips. A precise sequence of muscle activity, starting in the lower body, is required to transmit energy to the ball. Baseball pitchers complete thousands of throws to learn the skills necessary to execute a fastball, curveball, and the many other throws needed to play the game. Each of these throws results in high forces in the arm and especially in the shoulder joint, and pitchers are susceptible to significant shoulder injuries from repetitive stress; for example, in order to achieve ball velocity of 90 mph, the shoulder must rotate at angular velocities of up to 7000°/sec and may be exposed to forces of up to 950 N. In elite-level pitchers, there is a balance that must be achieved between the shoulder mobility that is necessary to reach extreme positions of rotation so that velocity can be transmitted to the ball and the stability that is necessary to keep the humeral head within the glenoid socket and prevent injuries. Body rotation, timing, and positioning of the scapula are all key components of the throwing motion, and any alterations to this motion will have a compounded effect on the shoulder (see Brun et al., J. Bone J. Surg. 91 (2009)).

[0097] A successful pitch involves both ball velocity and precision. Ball velocity is most directly dependent on the amount of external rotation achieved in the shoulder, while precision (the ability to throw the ball at a specific location) is dependent on the pitcher’s specific arm position and timing of ball release. The entire pitching motion consists of 6 phases: windup, early cocking, late cocking, acceleration, deceleration, and follow-through, with most injuries occurring during late cocking, acceleration, and deceleration (see FIG. 10). As a result of the extensive research conducted on pitching biomechanics, there are many different parameters that may be monitored during a pitch. This Example focuses on a select few parameters during the late cocking, acceleration, and deceleration phases that are most critical to injury and performance.

[0098] During late cocking, the shoulder should be between 90° and 100° of abduction, and should remain in this position for the rest of the critical phases. Also during this phase, the arm should rotate from a position of approximately 50° of external rotation to about 175° at maximum external rotation, allowing the pitcher to apply a significant force to the ball. In terms of muscle activation, the subscapularis, pectoralis major, and latissimus dorsi provide stability to the glenohumeral joint and should apply an anterior force and an internal rotation torque to stabilize the joint. The next phase, acceleration, should last only approximately 42 to 58 ms. The shoulder should be internally rotated, moving from 175° of external rotation to 90° or 100° of external rotation at ball release. The angular velocity of this internal rotation should be a maximum of between 6000°/sec and 7000°/sec. The subscapularis exhibits high activity to position the humeral head and prevent subluxation, and high activity in the teres minor helps to stabilize the joint by forming a force couple with the pectoralis muscle to limit humeral head translation (see Park et al., Bull. Hosp. Jt. Dis. 61:1-2 (2002-2003)). In the deceleration phase (50 ms after ball release), the shoulder should continue rotating internally until the arm reaches a position of 0°. The internal rotation angular velocity should also decrease to 0°/sec. The arm should rapidly abducted about the shoulder to a position of approximately 110°. The teres minor should exhibit the highest level of activity as it acts to decelerate the arm by eccentric contraction as well as stabilize the joint to limit humeral head translation (see Park et al., Bull. Hosp. Jt. Dis. 61:1-2 (2002-2003)).

[0099] These parameters indicate that four measurements of the shoulder joint are critical for pitching biomechanics: timing of the movement, joint angles, joint angular velocity, and muscle activation. As such, the invention described here can be used to monitor and provide feedback to the subject about these parameters immediately after the execution of the throw (similar to the method described in Example 1). The Measurement Module comprises inertial measurement units containing accelerometers and gyroscopes placed on the subject’s shoulder and upper arm. Additional hardware in the form of surface electromyography (EMG) electrodes are also placed on the critical muscles (subscapularis, teres minor, etc) to measure muscle activation. The Processing Module includes calibration routines to identify the locations of the sensors on the body, align the sensors in relation to one another and to the global reference frame, and determine the maximum muscle activations. The initial starting position of the arm is measured to determine the reference/neutral position for that subject. The gyroscope and accelerometer measurements are combined together (using the method described in Example 1) to measure the kinematics of the shoulder and arm (internal/external rotation at the shoulder). The gyroscopes in the inertial measurement units measure the speed of the movement of the arm by measuring the segment angular velocity (similar to Example 1), and the surface electromyography electrodes measure the muscle activation. Timing is measured by the internal processor clock.

[0100] Temporal features and discrete metrics are calculated, and then a comparison model similar to the one described in Examples 1 and 2 is used. Ideal values for each of the discrete metrics are programmed into the model and the differences between the discrete metrics from the subject’s movement and the target metrics are the basis of the risk and performance evaluation.

[0101] The Feedback and Display Module consists of providing feedback to the subject immediately following the completion of the throw (similar to Example 1). Since the ideal throwing motion consists of ranges of acceptable values
for each parameter, the type of feedback given to the subject may resemble the feedback provided in example 1. Visual
feedback may consist of graphs showing the subject’s actual motion versus the ideal motion. The subject may watch a
video of the ideal movement superimposed over their actual movement so that they can assess timing and angular deviations
in their movement. For example, for the internal rotation of the arm, the subject might see how their measurements compare to the target execution on a graph, with their previous history also shown to represent their progress (similar to FIG. 5). Haptic feedback to the subject might consist of vibration devices placed on the muscles measured with the surface electromyography electrodes; these devices could deliver vibratory feedback to remind the subject to focus on activating those muscles. For timing of the motion, the subject may receive auditory feedback indicating how quickly the difference phases of the motion should be completed. Altogether, teaching a subject the proper technique for throwing a baseball is yet another embodiment of the present invention and may be used for immediate measurement, analysis, and feedback in order to prevent injuries and improve performance.

Example 4

Reduction of Work-Related Back Injury

It is widely documented that back injury due to occupational tasks (e.g., muscle, tendon, or ligament strains or sprains) is a significant socio-economic concern. For example, based on a monograph from the National Institute for Occupational Safety and Health (NIOSH), Monroe Keyserling (American Industrial Hygiene Association, 61: 39-50, 2000) reported that 32% of the injury and illness cases involving days away from work resulted from overexertion or repetitive motion. Moreover, 75% of these cases were associated with manual materials handling (e.g., lifting or pushing), and 13% resulted from repetitive motion (e.g., data entry tasks or repetitive use of tools). While the actual risk factors differ among occupational tasks, inappropriate posture and execution of movement are almost always associated with increased risks for back injury.

Although ideal posture and movement execution depend on the task, some general biomechanical parameters associated with the risks for back injury have been identified, such as the trunk posture and movement, arm elevation, coordination between the segments, muscle activation and fatigue, and frequency of the repetition (Wrigley et al., Clinical Biomechanics 20: 254-263 (2005); Marras et al., Spine, 18: 617-628 (1993)). The risks associated with these parameters in isolation and with their interactions are different from task to task. Therefore, this Example is a representative embodiment of the invention where the hardware used to measure, analyze, evaluate, and provide feedback can be used for many different tasks without any significant modification; only the algorithms to process the signals from the sensors and the variables to control the feedback need to be adjusted. In this Example, the invention is used to monitor and provide real-time feedback to a subject during the execution of a repetitive occupational task to reduce his or her risk for back injury.

The Measurement Module consists of inertial measurement units containing accelerometers and gyroscopes placed on the pelvis, lower-trunk, upper-trunk, upper-arm, forearm, and head. In addition, surface electromyography electrodes are placed on important muscles of the trunk and arms, such as the longissimus, iliocostalis, trapezius, and deltoid. For some particular tasks, pressure outsoles, pressure mats fixed on the seat slip, or pressure gloves are also included.

The Processing Module includes calibration routines to identify the locations of the sensors on the body, align the sensors with the segment frame, determine the maximum muscle activations, and set the initial pressure conditions. Then the Processing Module combines the signals from the sensors to obtain specific continuous descriptive parameters. The parameters quantifying the kinematics consist of the angles, angular velocities, and angular accelerations of the pelvis, lower-trunk, upper-trunk, upper-arm, forearm, and head segments in the three anatomical planes (i.e., flexion, abduction, and rotation). Continuous descriptive parameters for the angular movement of the joints are also calculated, in terms of angles, angular velocities, and angular accelerations. Based on the surface electromyography signals and/or pressure sensors, kinematic continuous descriptive parameters of the segments are obtained. In addition, discrete metrics such as the frequency of the repetition are determined.

This embodiment of the invention provides real-time feedback during the execution of the movement (similar to Example 2); as such, the values of the continuous parameters at each time sample are considered as discrete metrics and constitute the input of the comparison model. Depending of the task under analysis, the comparison model can simply compare the metrics with target values. In terms of a lifting task, the level of risk is related to the amount of rotation of the upper-trunk relative to the pelvis: a large rotation towards the right, a large rotation towards the left, or a large overall amplitude of rotation are risk factors for back injury. Alternatively, the comparison model can use a data manipulation algorithm, such as a neural network or a principal component analysis. For example, while sitting at a computer, the flexion between the pelvis and the lower-trunk, the flexion between the lower-trunk and the upper-trunk, the flexion between the upper-trunk and the head, the elevation of the upper-arms, the intensity of the surface electromyography signals of the erector spinae muscles, and the pressure recorded by the mat on the chair can be analyzed by a neural network previously trained to estimate the overall adequacy of the posture. For this task, an awkward posture is associated with a higher risk of back injury.

The Feedback and Display Module consists of true immediate feedback (similar to Example 2), meaning that the subject receives feedback during the movement and he or she can continuously adjust how he or she is completing the occupational task. Feedback given during the execution of the movement is especially beneficial for reduction of back injury during occupational activities because it does not require the subject to stop after every couple of repetitions to look at his or her risk evaluation. Instead, the subject can perform his or her repetitive task normally; if the execution is not appropriate, a feedback signal is activated. The feedback provided may be a combination of a vibration device and auditory
device. Overall, training a subject in the proper technique for reducing the risk for back injury provides another excellent example of how the present invention may be used for immediate measurement, analysis, and feedback in order to evaluate risk and prevent injuries.

[0109] For the Recording Module of this embodiment of the invention, the raw and adjusted signals from the sensors, the time continuous parameters, the discrete metrics, the feedback variables, and the feedback targets are stored in a memory for each time sample.

[0110] The preceding merely illustrates the principles of the invention. It will be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and conditional language recited herein are principally intended to aid the reader in understanding the principles of the invention and the concepts contributed by the inventors to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention as well as specific examples thereof, are intended to encompass both structural and functional equivalents. Additionally, it is intended that such equivalents include both currently known equivalents and equivalents developed in the future; i.e., any elements developed that perform the same function, regardless of structure. The scope of the present invention, therefore, is not intended to be limited to the exemplary aspects shown and described herein. Rather, the scope and spirit of present invention is embodied by the appended claims. In the claims that follow, unless the term “means” is used, none of the features or elements recited therein should be construed as means-plus-function limitations pursuant to 35 U.S.C. §112, ¶6.

We claim:

1. A method for training a subject to avoid joint injuries, comprising:
   - gathering raw data from at least one sensor attached to a subject, to an interface, or in the subject’s environment where the at least one sensor allows quantifying at least one parameter associated with a movement known to correspond to a risk of joint injury;
   - transmitting the raw data to at least one processor;
   - evaluating the risk of injury by comparing the raw data or processed raw data to a stored model;
   - providing feedback to the subject based on the evaluated risk of injury so the subject can alter the movement and reduce the risk of joint injury; and
   - storing at least one of the raw data, the processed raw data, the evaluated risk data and the feedback data.

2. The method of claim 1, wherein at least five sensors or more are used.

3. The method of claim 2, wherein at least ten sensors or more are used.

4. The method of claim 1, wherein the at least one sensor is a gyroscope, an accelerometer, a magnetometer, an electrode, a pressure sensor, a force sensor, a torque sensor, a force platform, a speed sensor, a goniometer, a camera, or a thermometer.

5. The method of claim 1, wherein the movement is performed during walking, jogging, running, jumping, throwing, swinging, kicking, swimming, rowing, squatting, lifting, pushing, climbing, cutting, blocking, skiing, snowboarding, punching, sitting, typing, cycling, or dancing.

6. The method of claim 1, wherein the at least one parameter is selected from joint kinematics, joint kinetics, body segment posture, body segment kinematics, body segment kinetics.

7. The method of claim 6, wherein the at least one parameter is selected from ankle flexion, eversion, rotation angle, angular velocity, angular acceleration, force, moment, or power;
   - knee flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power;
   - hip flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; spine flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; shoulder flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; elbow flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; wrist flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power;
   - neck flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; foot position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; shank position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; thigh position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; pelvis position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; trunk position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; upper arm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; forearm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; hand position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; or head position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk.

8. The method of claim 6, wherein the at least one parameter is selected from force, pressure, or moment between the subject and an interface or the environment.

9. The method of claim 6, wherein the at least one parameter is selected from muscle activity.

10. The method of claim 1, wherein the feedback provided is visual.

11. The method of claim 10, wherein the feedback provided is a graph.

12. The method of claim 10, wherein the feedback provided is an avatar.

13. The method of claim 10, wherein the feedback provided is three dimensional.

14. The method of claim 1, wherein the feedback provided is auditory.

15. The method of claim 1, wherein the feedback provided is tactile or haptic.

16. The method of claim 1, wherein the joint injury is selected from a joint injury to a knee, elbow, wrist, ankle, hip, shoulder, or spine.
A body movement training system comprising:

- at least one sensor configured to measure at least one parameter associated with a movement known to correspond to risk of joint injury;
- transmitters associated with the at least one sensor to transmit raw data related to the at least one parameter to at least one processor;
- at least one processor configured to receive the raw data from the transmitters, process the raw data, compare the raw data or processed raw data to a stored model, evaluate the risk of joint injury based on the comparison of the raw data or processed raw data to the stored model, and generate feedback data;
- a display or interface device to provide immediate feedback to the subject based on the feedback data so the subject can alter the movement and reduce the risk of joint injury; and
- a storage medium to record the raw data, the processed raw data, the evaluated risk data and the feedback data.

The body movement training system of claim 17, wherein at least five or more sensors are used.

The body movement training system of claim 18, wherein at least ten or more sensors are used.

The body movement training system of claim 17, wherein the at least one sensor is a gyroscope, an accelerometer, a magnetometer, an electrode, a pressure sensor, a force sensor, a torque sensor, a force platform, a speed sensor, a goniometer, a camera, or a thermometer.

The body movement training system of claim 17, wherein the movement measured is performed during walking, jogging, running, jumping, throwing, swinging, kicking, swimming, rowing, squatting, lifting, pushing, climbing, cutting, blocking, skiing, snowboarding, punching, sitting, typing, cycling, or dancing.

The body movement training system of claim 17, wherein the at least one parameter is selected from joint kinetics, joint kinematics, body segment posture, body segment kinematics, body segment kinetics.

The body movement training system of claim 17, wherein the at least one parameter is selected from ankle flexion, eversion, rotation angle, angular velocity, angular acceleration, force, moment, or power; knee flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; hip flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; spine flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; shoulder flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; elbow flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; wrist flexion, abduction, rotation angle, angular velocity, angular acceleration, force, moment, or power; neck flexion, lateral bending, rotation angle, angular velocity, angular acceleration, force, moment, or power; foot position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; shank position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; thigh position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; pelvis position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; upper arm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; hand position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; forearm position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk; head position, velocity, acceleration, jerk, orientation, angular velocity, angular acceleration, or angular jerk.

The body movement training system of claim 17, wherein the at least one parameter is selected from force, pressure, or moment between the subject and an interface or the environment.

The body movement training system of claim 17, wherein the feedback provided is visual.

The body movement training system of claim 17, wherein the feedback provided is a graph.

The body movement training system of claim 17, wherein the feedback provided is auditory.

The body movement training system of claim 17, wherein the feedback provided is tactile or haptic.

* * * *