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Provisional Patent Application under 35 U.S.C. § 111(b)

FORCE-CONTROLLED CABLE-DRIVEN STRETCHING APPARATUS WITH VISION-BASED COMPENSATION DETECTION AND ADAPTIVE LONGITUDINAL PROTOCOL

Specification — Provisional Application under 35 U.S.C. § 111(b)

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This is a provisional patent application filed under 35 U.S.C. § 111(b). No related applications are cross-referenced at the time of this filing.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable. This invention was not made with United States Government support.

REFERENCE TO SEQUENCE LISTING, TABLE, OR COMPUTER PROGRAM LISTING COMPACT DISC APPENDIX

[0003] Not applicable.

FIELD OF THE INVENTION

[0004] The present invention relates generally to athletic training, rehabilitation, and assisted stretching devices. More particularly, the invention relates to a motorized, cable-driven apparatus that applies controlled tensile force to a limb of a human subject while concurrently measuring biomechanical parameters including joint range of motion, cable force, and movement compensation, and that adjusts applied force in real time based on vision-detected compensatory motion. The invention further relates to methods of bilateral assessment, longitudinal flexibility tracking, injury risk scoring, and adaptive protocol modification using the data acquired during such stretching sessions.

BACKGROUND OF THE INVENTION

A. The Clinical Problem

[0005] Soft-tissue injuries, and in particular muscle strains affecting the hamstrings, adductors, quadriceps, hip flexors, and calves, are among the most prevalent and costly injuries in professional and collegiate athletics. Longitudinal epidemiological data from the Union of European Football Associations (UEFA) Elite Club Injury Study documents that hamstring injuries alone have doubled as a percentage of total injuries over a twenty-one year observation period, rising from approximately twelve percent (12%) to twenty-four percent (24%) of all recorded injuries, with training-incurred injuries rising approximately 6.7% annually despite advances in strength and conditioning science.

[0006] Similar trends have been documented across other elite sports. A twelve-year review of 2,101 hamstring injuries in the National Football League reported that approximately twenty-five percent (25%) of players sustain at least one lower-extremity strain per season, with re-injury rates exceeding thirty percent (30%). In professional association football, approximately twenty-one percent (21%) of players suffer a groin or adductor injury per season, of which sixty-eight percent (68%) are adductor-related. Systematic reviews further establish that restricted hip internal rotation and restricted ankle dorsiflexion are independent biomechanical risk factors for anterior cruciate ligament (ACL) injury.

[0007] The economic consequences are substantial. Top tier association football clubs report losses exceeding seven million Euros (€7M) per annum attributable to muscle injuries. In the English Premier League during the 2023-2024 season, aggregate player wages paid to sidelined athletes exceeded two hundred sixty-six million pounds (£266M), of which eighty-three million pounds (£83M) was attributable to hamstring injuries alone.

B. Limitations of the Prior Art

[0008] Despite the documented clinical and economic significance of soft-tissue injury, the assessment and treatment of joint flexibility and muscle extensibility in elite athletic settings remain substantially unchanged since the adoption of clinical goniometry in the mid-twentieth century. The prior art devices and methods suffer from several fundamental limitations that the present invention addresses.

[0009] *Manual goniometry.* Conventional joint angle measurement is performed using a manual goniometer operated by a clinician. Published inter-rater reliability studies demonstrate errors of five to ten degrees (5°–10°) depending on joint, clinician experience, and soft tissue palpability. Measurements are recorded on paper or entered manually into an athlete management system, introducing transcription error and preventing real-time comparison. No standardized applied force is used, so the joint angle measured represents end-range tolerance for that clinician's specific applied pressure, which varies between sessions and clinicians.

[0010] *Manual assisted stretching.* Assisted stretching performed by a clinician or partner lacks force standardization, creates clinician fatigue over multi-hour sessions affecting large rosters, and produces no quantitative record of applied force, range of motion, or compensation. Compensatory motion by the athlete (pelvic rotation, knee flexion, trunk shift) is judged by eye and frequently missed.

[0011] *Isokinetic dynamometers (e.g., Biodex, Cybex).* Clinical isokinetic devices measure torque and angular velocity but are designed for strength assessment under concentric and eccentric loading, not for sustained static stretching. They are expensive (frequently exceeding one hundred thousand United States dollars, $100,000), lack integrated vision-based compensation detection, and do not implement force-controlled passive stretching protocols suitable for pre-practice or recovery use.

[0012] *Pneumatic compression devices (e.g., Normatec).* Compression devices provide passive recovery modalities but do not apply a directed tensile stretch, do not measure joint range of motion, and do not generate biomechanical data relevant to flexibility assessment.

[0013] *Manual stretching services (e.g., StretchLab).* Franchise-based manual stretching services provide one-to-one assisted stretching but produce no objective measurement, no protocol consistency across providers, and no longitudinal record suitable for trend analysis or injury risk assessment.

[0014] *Computer vision goniometry applications.* Mobile-device applications exist that estimate joint angles from two-dimensional video. Such applications suffer from substantial parallax error inherent to monocular two-dimensional capture, lack a standardized force input, are not integrated with a motorized stretching apparatus, and do not close a feedback loop between measured compensation and applied force.

[0015] *Cable-drive fitness devices.* Motorized cable-drive resistance training devices exist in the prior art for strength training (for example, devices marketed under the name "Vitruvian Trainer" and "Tonal"). Such devices apply resistance against concentric muscle action for strength training. They do not apply passive directed tensile force for stretching, do not implement vision-based compensation detection, and do not integrate joint-angle measurement with force application for flexibility assessment.

[0016] Accordingly, there exists a need in the art for an apparatus and associated methods that (a) apply controlled, standardized tensile force to a limb of a human subject for the purpose of assisted stretching, (b) concurrently measure joint range of motion and movement compensation in real time, (c) close a feedback loop between detected compensation and applied force to prevent unsafe or biomechanically invalid stretching, (d) generate a standardized, exportable quantitative record of each session, and (e) use longitudinal session data to produce individualized injury risk scoring and adaptive protocol modification. The present invention satisfies these needs.

BRIEF SUMMARY OF THE INVENTION

[0017] The present invention provides an apparatus, system, and method for force-controlled assisted stretching with vision-based compensation detection and adaptive longitudinal protocol modification. In one embodiment, the apparatus comprises a support frame, a brushless direct-current (BLDC) motor coupled through a planetary gearbox to a cable spool, a flexible cable wound on the spool and terminating in a quick-release cuff adapted to engage a limb of a human subject, an inline force sensor arranged along the cable, a depth-sensing camera arranged to observe the subject, a motor controller configured to execute a proportional-integral-derivative (PID) force control loop, and a computing system configured to process depth data from the camera to extract a skeletal model of the subject and detect compensatory motion.

[0018] In a principal aspect of the invention, the computing system is configured to classify compensatory motion and to transmit a compensation signal to the motor controller that modifies the force setpoint of the PID loop in real time, such that the applied cable tension is automatically reduced when compensation is detected. This closed-loop coupling between vision-based compensation detection and force control constitutes a significant and non-obvious improvement over the prior art.

[0019] In a further aspect, the apparatus implements a five-layer independent safety cascade comprising: (1) a software force cap, (2) a PID compliance loop with anti-windup, (3) a mechanical slip clutch between the gearbox output and the spool, (4) a hardwired emergency stop circuit, and (5) a quick-release cuff mechanically detachable from the cable. Each layer operates independently and may halt the stretch without reliance on any other layer.

[0020] In a further aspect, the apparatus is reconfigurable to perform a plurality of stretch patterns from a single drive system without modification of the motor, gearbox, cable, or spool. In a first version configuration, the apparatus serves four stretch patterns through athlete repositioning relative to a fixed pulley. In a second version configuration, the apparatus additionally serves three further stretch patterns through engagement of an adjustable pulley mounted on a sliding track.

[0021] In a further aspect, the method of the invention comprises a bilateral assessment protocol in which a standardized passive stretch is applied to a first limb at a standardized force, a peak joint angle is measured, the same standardized stretch is applied to the contralateral limb, a bilateral asymmetry is calculated as the absolute difference between the two peak angles, and an asymmetry flag is raised when the difference exceeds a threshold. The method further comprises the storage of nine measurement variables per repetition including peak joint angle, cable force, bilateral asymmetry, hold time, compensation flags, tolerance threshold, pain response, tension ramp rate, and session delta, and the generation of a longitudinal injury risk score based on time-series analysis of said variables.

[0022] In a further aspect, the system implements an adaptive protocol engine that uses longitudinal session data to modify protocol parameters (force setpoint, hold time, number of repetitions, pattern selection) for subsequent sessions of the same subject, such that the protocol individualizes to the subject’s biomechanical profile over time.

[0023] The foregoing is a non-limiting summary. Additional features, aspects, and advantages of the invention will become apparent from the following detailed description and the appended claims, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The accompanying drawings are incorporated into and form a part of this specification. The drawings illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention. The drawings are not drawn to scale unless specifically noted.

[0025] **FIG. 1** is a system-level block diagram illustrating the principal functional elements of the apparatus and their signal interconnections, including the novel compensation feedback path from the vision system to the PID controller.

[0026] **FIG. 2** is a side-elevation schematic of one embodiment of the apparatus, showing the arrangement of the motor, gearbox, cable spool, load cell, cuff, depth camera, touchscreen, emergency stop, and support frame.

[0027] **FIG. 3** is a flow diagram illustrating one embodiment of the bilateral assessment method, including the steps of subject identification, bilateral baseline measurement, asymmetry calculation, stretch protocol execution with closed-loop control, data logging, report generation, and longitudinal feedback.

[0028] **FIG. 4** is a detail schematic of the cable drive assembly, showing the BLDC motor, planetary gearbox, cable spool, mechanical slip clutch, flexible cable, and ODrive field-oriented control (FOC) motor controller.

[0029] **FIG. 5** is a schematic of the sensor array and data paths, showing the depth camera, inline load cell, edge compute module, touchscreen interface, and cloud storage link.

[0030] **FIG. 6** is a schematic of the control interface architecture, showing the session user interface, live display, trend view, and local data bus.

[0031] **FIG. 7** is a schematic of the five-layer safety cascade, showing each independent safety layer with characteristic response time.

[0032] **FIG. 8** is a schematic of the measurement extraction pipeline, showing the three raw sensor inputs, the sensor fusion stage, the nine derived measurement variables, and the longitudinal risk score engine.

[0033] **FIG. 9** is a schematic of the multi-pattern reconfigurable platform, showing four V1 stretch patterns served by a fixed pulley and three V2 stretch patterns served by an adjustable pulley on a sliding track.

[0034] **FIG. 10** is a detail block diagram of the PID force-compliance control loop, showing the summing junction, PID controller, force cap, motor drive, plant, load cell feedback path, and compensation signal input.

[0035] **FIG. 11** is a detail flow diagram of the compensation detection and adaptive force response algorithm, showing the depth frame input, pose model, joint angle calculation, compensation classifier, and force setpoint modification output.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0036] Reference will now be made in detail to preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the invention will be described in conjunction with these preferred embodiments, it will be understood that they are not intended to limit the invention to these embodiments. On the contrary, the invention is intended to cover alternatives, modifications, and equivalents that may be included within the spirit and scope of the invention as defined by the appended claims.

[0037] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the invention. The invention may be practiced without some or all of these specific details. In other instances, well-known structures, devices, protocols, and data formats have not been described in detail in order to avoid unnecessarily obscuring aspects of the invention. Where the term "preferred" is used, the invention is not limited to the preferred example.

[0038] As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural reference unless the context clearly dictates otherwise. The word "or" is used in the inclusive sense except where the context indicates otherwise. The term "comprising" and its grammatical equivalents are used in the open-ended sense, as are "including," "containing," "having," and "characterized by." All numerical ranges are inclusive of their endpoints unless specifically noted.

1. Reference Numeral Index

[0039] The following table provides an index of reference numerals used throughout the drawings and the detailed description. Reference numerals are assigned using even integers consistent with United States Patent and Trademark Office drafting conventions.

Numeral	**Element**	**Principal Figures**
10	Brushless direct-current (BLDC) motor	FIG. 2, FIG. 4
12	Planetary gearbox (20:1 reduction)	FIG. 2, FIG. 4
14	Cable spool	FIG. 2, FIG. 4
16	Inline load cell (force sensor)	FIG. 2, FIG. 4, FIG. 10
18	Quick-release cuff	FIG. 2, FIG. 7
20	Depth-sensing camera	FIG. 2, FIG. 5
22	Touchscreen display	FIG. 2, FIG. 6
24	Emergency stop switch	FIG. 2, FIG. 7
26	Support frame and bench	FIG. 2
30	Motor power stage	FIG. 4
32	Gearbox output shaft	FIG. 4
34	Cable spool (drive-side detail)	FIG. 4, FIG. 9
36	Mechanical slip clutch	FIG. 4, FIG. 7
38	Flexible cable	FIG. 4, FIG. 9
40	Depth camera (sensor-detail)	FIG. 5, FIG. 9
42	Load cell (sensor-detail)	FIG. 5
44	Edge compute module (Jetson-class)	FIG. 5

Numeral	**Element**	**Principal Figures**
46	Touchscreen (sensor-detail)	FIG. 5
48	Cloud storage link	FIG. 5
50	Session user interface module	FIG. 6
52	Live display module	FIG. 6
54	Trend view module	FIG. 6
60	Sensor fusion engine	FIG. 8
62	Longitudinal risk score engine	FIG. 8
100–112	Method steps (bilateral assessment)	FIG. 3
200	Athlete identification module	FIG. 1
202	Protocol engine	FIG. 1
204	PID force controller	FIG. 1, FIG. 10
206	Cable drive subsystem	FIG. 1
208	Athlete (subject)	FIG. 1
210	Vision system	FIG. 1, FIG. 11
212	Data engine	FIG. 1
214	Adaptive feedback path	FIG. 1
220	Pose estimation model	FIG. 11

Numeral	**Element**	**Principal Figures**
222	Joint angle calculation module	FIG. 11
224	Compensation classifier	FIG. 11

2. System Overview (FIG. 1)

[0040] Referring now to FIG. 1, a system-level block diagram of an apparatus according to a preferred embodiment of the invention is shown. The apparatus is organized into eight principal functional modules interconnected as illustrated. A subject is first identified at the athlete identification module **(200)**, which receives input from a badge reader, fingerprint sensor, or other unique identifier, and retrieves from a database the subject's profile, prior session history, and current training context. The subject profile is passed to a protocol engine **(202)**, which determines the stretch pattern to be applied and the initial force setpoint F_{set} based on the subject's profile and the selected session type.

[0041] The force setpoint is transmitted from the protocol engine **(202)** to the PID force controller **(204)**. The PID force controller drives the cable drive subsystem **(206)**, which applies tensile force to the subject **(208)**. The cable drive subsystem is instrumented with an inline load cell providing a measured force value F_{meas}, which is transmitted back to the PID force controller **(204)** at a sample rate of one hundred Hertz (100 Hz) to close the force control loop.

[0042] Concurrently, the vision system **(210)**, comprising a depth-sensing camera and associated computer vision software, observes the subject **(208)**. The vision system extracts a skeletal model of the subject, computes joint angles from the skeletal model, and applies a compensation classifier to detect compensatory motion. When compensation is detected, the vision system **(210)** transmits a compensation signal to the PID force controller **(204)** that modifies the force setpoint. This closed-loop coupling between vision-detected compensation and force control, illustrated in FIG. 1 as the path from **(210)** to **(204)**, constitutes a principal novel aspect of the invention.

[0043] Measurement outputs from the PID force controller **(204)**, cable drive subsystem **(206)**, and vision system **(210)** are aggregated at the data engine **(212)**, which stores the measurement variables described in greater detail in the discussion of FIG. 8 herein below, computes longitudinal trends, and produces an injury risk score. An adaptive feedback path **(214)** connects the data engine **(212)** back to the protocol engine **(202)**, such that the historical data for the subject modifies the protocol parameters used in subsequent sessions.

3. Apparatus Configuration (FIG. 2)

[0044] Referring now to FIG. 2, a side-elevation schematic of one embodiment of the apparatus is shown. The apparatus comprises a support frame and bench assembly **(26)**, which provides structural support for the drive assembly and a planar surface on which the subject may lie in a supine, prone, or lateral position. In the illustrated embodiment, the support frame comprises a vertical upright coupled to a horizontal base, with the bench surface arranged substantially parallel to and spaced above the base.

[0045] Mounted at the upper end of the vertical upright is the BLDC motor **(10)**, having a nominal continuous power rating of two hundred Watts (200 W). The motor output shaft is coupled to the input of a planetary gearbox **(12)** having a reduction ratio of twenty to one (20:1). The output shaft of the gearbox is coupled to a cable spool **(14)** on which a flexible cable is wound. In a preferred embodiment, the cable comprises ultra-high-molecular-weight polyethylene fiber (commonly sold under the designation "Dyneema") having a minimum breaking strength of at least two thousand pounds-force (2,000 lbf) and a diameter in the range of two to four millimeters (2–4 mm).

[0046] The cable extends from the spool, is routed over one or more pulleys as described in further detail in connection with FIG. 9 herein below, passes through an inline load cell **(16)**, and terminates in a quick-release cuff **(18)** adapted to engage a limb of the subject. The load cell is a strain-gauge transducer calibrated to output an electrical signal proportional to tensile force applied to the cable, with a sample rate of one hundred Hertz (100 Hz) and a full-scale range selected to cover zero to fifty pounds-force (0–50 lbf).

[0047] The quick-release cuff **(18)** comprises a padded neoprene or equivalent compliant body, an adjustable strap with hook-and-loop closure, and a quick-release connection to the cable terminus. In a preferred embodiment, the quick-release connection is a carabiner or a spring-loaded clevis that can be disengaged with a single hand in less than one second. The cuff is dimensioned to distribute cable tension across a minimum contact area of fifty square centimeters (50 cm^2) to avoid localized tissue pressure.

[0048] The depth-sensing camera **(20)** is mounted on the vertical upright at a height and angle selected such that the field of view of the camera encompasses the subject’s body from pelvis to the distal end of the stretched limb. In a preferred embodiment, the camera is an Intel RealSense D435 stereoscopic depth camera, or functional equivalent, having a depth image resolution of at least 640 by 480 pixels at a frame rate of at least thirty frames per second (30 fps), a depth range of 0.3 to 3.0 meters, and a horizontal field of view of at least 85 degrees.

[0049] A touchscreen display **(22)** is mounted to the frame at a location readily visible and accessible to the subject, staff operator, or both. The touchscreen comprises a capacitive or resistive touch-sensitive panel overlaying a liquid-crystal or organic lightemitting-diode display of at least 15-inch (38.1 cm) diagonal dimension. The touchscreen displays the session user interface, live force and range-of-motion values, and longitudinal trend data as further described in connection with FIG. 6.

[0050] An emergency stop switch **(24)** is mounted at a prominent location accessible to both the subject and the staff operator. The emergency stop comprises a mushroom-head push button of the normally-closed, mechanically-latching type. Activation of the emergency stop directly interrupts electrical power to the motor power stage by hardwired circuit, independent of any software.

4. Bilateral Assessment Method (FIG. 3)

[0051] FIG. 3 illustrates a preferred method of operation of the apparatus for bilateral longitudinal assessment of a subject. The method comprises, in sequence, a subject identification step **(100)**, a left-limb baseline measurement step **(102)**, a right-limb baseline measurement step **(104)**, an inter-limb asymmetry calculation step **(106)**, an assisted stretch protocol step **(108)**, a data logging step **(110)**, and a longitudinal feedback step **(112)**.

[0052] In the subject identification step **(100)**, the subject is identified to the system by one or more of: (i) presentation of a radio-frequency identification (RFID) token; (ii) entry of a numeric or alphanumeric identifier on the touchscreen **(22)**; (iii) biometric identification via fingerprint, facial recognition from the depth camera **(20)**, or equivalent; or (iv) selection from a roster of enrolled subjects. Upon successful identification, the system retrieves the subject's longitudinal measurement record from a non-transitory data store.

[0053] In the left-limb baseline measurement step **(102)**, the apparatus commands a controlled low-force traction of the left limb along a predetermined pattern while the depth camera **(20)** captures the joint trajectory and the load cell **(16)** captures the applied force. The baseline range-of-motion terminus is defined as the joint angle at which the subject's selfreported perceived tension reaches a predetermined level, or at which an involuntary compensatory motion is first detected, whichever occurs first. The baseline measurement is performed at a controlled reference force, in a preferred embodiment between twelve (12) and eighteen (18) pounds-force, to ensure reproducibility across sessions.

[0054] The right-limb baseline measurement step **(104)** is performed immediately subsequent to the left-limb baseline, using identical protocol parameters and the identical reference force. The temporal separation between left and right baseline measurements is preferably less than three (3) minutes in order to minimize the confounding effects of neuromuscular fatigue and thermoregulatory drift on the comparative measurement.

[0055] In the asymmetry calculation step **(106)**, the system computes a bilateral asymmetry index defined as the absolute difference between the left and right baseline range-of-motion values, expressed as a percentage of the greater of the two values. An asymmetry exceeding a predetermined threshold, in a preferred embodiment ten percent (10%), triggers an injury-risk flag that is displayed to the operator and written to the subject’s longitudinal record. This step produces, as a further output, a recommended modification to the subsequent stretch protocol such that the deficit limb receives extended or higher-intensity loading relative to the surplus limb.

[0056] In the assisted stretch protocol step **(108)**, the apparatus executes a force-controlled stretch cycle in accordance with the method of FIG. 10 (described below) and the pattern selection described in connection with FIG. 9. During the stretch protocol, compensation-aware force adjustment is performed in real time in accordance with the method of FIG. 11 (described below). The stretch protocol terminates upon reaching one of: (i) a prescribed target force; (ii) a prescribed target joint angle; (iii) a prescribed hold duration; (iv) operator termination via the touchscreen **(22)**; or (v) activation of any layer of the safety cascade of FIG. 7.

[0057] In the data logging step **(110)**, the system writes a complete session record to the non-transitory data store. The session record comprises, at minimum: (a) subject identifier; (b) session timestamp with sub-second resolution; (c) pattern selection; (d) prescribed and actual force time series sampled at not less than 100 Hz; (e) joint angle time series sampled at not less than 30 Hz; (f) computed compensation signal time series; (g) measured bilateral asymmetry index; (h) derived measurement variables V1 through V9 as defined in connection with FIG. 8; and (i) operator identifier and any exception or safety events.

[0058] In the longitudinal feedback step **(112)**, the system compares the session record to the subject's historical session records and computes one or more longitudinal trend outputs, including without limitation: (i) session-over-session change in range-of-motion at matched reference force; (ii) trend in bilateral asymmetry index; (iii) trend in tissue stiffness derived from the force-displacement slope; and (iv) a composite injury-risk score as further described in connection with FIG. 8. The longitudinal outputs are displayed to the subject and operator and are exported via application-programming-interface (API) endpoint to one or more external athlete-management systems.

5. Cable Drive Assembly (FIG. 4)

[0059] FIG. 4 depicts the cable drive assembly in greater detail. The cable drive assembly comprises the BLDC motor **(10)**, a field-oriented-control (FOC) motor controller **(30)**, the planetary reduction gearbox **(12)**, the cable spool **(14)**, a low-friction cable guide pulley **(32)**, the Dyneema synthetic cable **(34)**, the inline load cell **(16)**, a torque-limiting slip clutch **(36)** interposed between the gearbox output and the cable spool, and a manual quick-release mechanism **(38)** coupling the cable terminus to the cuff **(18)**.

[0060] The FOC motor controller **(30)** is a three-phase sinusoidal commutation controller implementing field-oriented vector control, in a preferred embodiment an ODrive Robotics S1 controller or functional equivalent. The controller receives a commanded torque set-point from the control processor and drives the motor **(10)** such that the instantaneous output torque matches the set-point to within five percent (5%) over the operating range. The controller samples the motor-phase currents at not less than eight thousand times per second (8 kHz) and closes an inner current loop at a bandwidth sufficient to maintain commanded torque during transient events.

[0061] The slip clutch **(36)** is a mechanical friction coupling preset to release at a predetermined torque corresponding to a cable tension not exceeding one hundred twenty percent (120%) of the maximum operational force. The slip clutch constitutes a purely mechanical safety layer, operative independent of electrical power or control software, and therefore provides a fail-safe behavior in the event of complete failure of the controller, the control processor, or the electrical supply.

[0062] The cable **(34)**, in a preferred embodiment, is a twelve-strand single-braid ultra-high-molecular-weight polyethylene rope having a diameter in the range of two to four millimeters (2–4 mm) and a minimum breaking strength of not less than two thousand pounds-force (2,000 lbf), thereby providing a safety factor exceeding forty (40) times the maximum operational force. The cable is routed from the spool **(14)**, over the cable guide pulley **(32)**, through the inline load cell **(16)**, and terminates at the quick-release mechanism **(38)**.

[0063] The quick-release mechanism **(38)** comprises a spring-loaded cam or clevis configured to disengage under a single-handed actuation force of less than twenty pounds-force (20 lbf) exerted by the subject or operator. Upon disengagement, the cuff **(18)** separates from the cable terminus in less than one (1) second, releasing the subject from the apparatus independent of any electrical or software system.

6. Sensor Array and Data Acquisition (FIG. 5)

[0064] FIG. 5 depicts the sensor array and associated data acquisition paths. The sensor array comprises the inline load cell **(16)** sampled by a first analog-to-digital converter **(40)**; the depth-sensing camera **(20)** communicating with a vision processing module **(42)**; a motor rotary encoder **(44)** integral to the motor **(10)**; a cable-drum rotary encoder **(46)** on the output side of the slip clutch **(36)**; and an optional surface electromyography (sEMG) electrode array **(48)** adapted to be adhered to selected muscles of the subject.

[0065] The load cell **(16)** comprises a strain-gauge bridge connected to a twenty-four-bit (24-bit) sigma-delta analog-to-digital converter **(40)**, preferably a Texas Instruments HX711 or equivalent, configured to sample cable tension at a rate of not less than one hundred samples per second (100 Hz). The load cell is calibrated in a range of zero to fifty pounds-force (0–50 lbf) with a resolution of 0.1 lbf.

[0066] The vision processing module **(42)** comprises executable software instructions running on the control processor that receive depth image frames and color image frames from the camera **(20)** at a rate of not less than thirty frames per second (30 fps) and extract therefrom a time-varying skeletal model of the subject. The skeletal model preferably comprises not less than twelve (12) joint centers including, without limitation, pelvis, hips (left and right), knees (left and right), ankles (left and right), shoulders (left and right), elbows (left and right), and wrists (left and right). From the skeletal model, the vision processing module computes a primary joint angle of interest, which, for a hamstring stretch pattern, is the hip-flexion angle θ computed as the two-argument arctangent of the vertical and horizontal offsets between the pelvis joint center and the ankle joint center.

[0067] The motor encoder **(44)** is a magnetic or optical incremental encoder having a resolution of not less than four thousand counts per revolution (4,000 CPR) and providing motor shaft position and velocity to the FOC controller **(30)** and to the control processor. The cable-drum encoder **(46)** is a second rotary encoder mechanically coupled to the output shaft downstream of the slip clutch **(36)**. Comparison of the motor encoder **(44)** position and the cable-drum encoder **(46)** position after reduction by the gearbox ratio provides an independent measurement by which slip of the clutch **(36)** is detectable in real time.

[0068] The optional sEMG electrode array **(48)**, when present, comprises wireless sEMG sensors applied to selected muscles (for a hamstring pattern: biceps femoris, gluteus maximus, and contralateral quadriceps) and sampled at not less than one thousand samples per second (1 kHz). The sEMG signal is band-pass filtered (preferably 20–450 Hz), rectified, and low-pass filtered to produce a muscle activation envelope used as an additional input to the compensation detection method of FIG. 11.

[0069] All sensor streams are time-stamped by a common monotonic clock maintained by the control processor to a precision of not less than one millisecond (1 ms) and are synchronized by a software synchronization service before being passed to the measurement extraction pipeline of FIG. 8.

7. Control Interface Architecture (FIG. 6)

[0070] FIG. 6 depicts the architecture of the control and user-interface subsystem. The subsystem comprises a control processor **(50)** embodied as a single-board computer; a local non-transitory data store **(52)** embodied as a solid-state storage device; a network interface **(54)**; the touchscreen display **(22)**; the FOC motor controller **(30)**; and the time-synchronized sensor bus described in connection with FIG. 5.

[0071] The control processor **(50)** is preferably a multi-core ARM64 or x86-64 single-board computer, such as an NVIDIA Jetson Orin Nano, a Raspberry Pi 5, or functional equivalent, executing a real-time or preemptive-scheduled operating system. The control processor is programmed with three principal software layers: (a) a real-time control layer that executes the closed-loop force control method of FIG. 10 at not less than one hundred iterations per second (100 Hz); (b) a vision and sensor-fusion layer that executes the method of FIG. 11 at the frame rate of the camera **(20)**; and (c) a session and user-interface layer that drives the touchscreen **(22)** and manages the session flow of FIG. 3.

[0072] The data store **(52)** retains all session records locally in an encrypted form, using a symmetric cipher of not less than 256-bit key length, such that the absence of network connectivity does not impair session execution or data logging. The data store has sufficient capacity to retain not less than twelve (12) months of daily sessions for a roster of not less than one hundred (100) enrolled subjects.

[0073] The network interface **(54)** provides wired and wireless connectivity to a remote server and to third-party athlete-management systems. The network interface transmits session records by an authenticated, encrypted transport (preferably Transport Layer Security version 1.3 or higher) to one or more application-programming-interface (API) endpoints. In preferred embodiments, the network interface supports integration with externally administered athlete-management platforms, including without limitation Smartabase, Kitman Labs, and Catapult Vector, by way of configurable REST or GraphQL adapters executed on the control processor.

[0074] The touchscreen display **(22)** presents a graphical user interface comprising at least: (i) a subject-facing mode displaying real-time force, range-of-motion, and remaining protocol time; (ii) an operator-facing mode displaying bilateral comparison plots, compensation indicators, and protocol configuration; and (iii) a longitudinal review mode displaying session-over-session trends of the variables of FIG. 8. The user interface is rendered as a web application served locally by the control processor **(50)** and displayed on a browser engine running on the touchscreen.

8. Five-Layer Safety Cascade (FIG. 7)

[0075] FIG. 7 depicts a five-layer safety cascade implemented by the apparatus. The cascade comprises, in order of first-to-act: (L1) a software maximum-force ceiling enforced within the real-time control layer of the control processor **(50)**; (L2) a proportional-integral-derivative (PID) compliance response triggered by detection of compensatory motion or force spikes, described in connection with FIG. 10 and FIG. 11; (L3) the mechanical slip clutch **(36)** of FIG. 4, set to release at one hundred twenty percent (120%) of maximum operational force; (L4) the hardwired emergency stop switch **(24)** of FIG. 2 cutting power directly to the motor power stage; and (L5) the manual quick-release mechanism **(38)** of FIG. 4 permitting the subject or operator to detach the cuff **(18)** from the cable within one second.

[0076] Each layer is independent of the layer below it in both cause and mechanism. Layer L1 executes in software at not less than 100 Hz and intervenes within ten milliseconds (10 ms) of a force-cap violation. Layer L2 executes in software at not less than 30 Hz and reduces commanded force within fifty milliseconds (50 ms) of a compensation detection or anomalous load-cell reading. Layer L3 is mechanical and slips whenever the through-torque exceeds its pre-set release torque, irrespective of software state. Layer L4, when activated, removes electrical energy from the motor power stage through a normally-closed mechanical contactor, without any involvement of the controller, processor, or software. Layer L5 is purely mechanical and hand-operable.

[0077] The five-layer cascade is characterized in that failure of any one layer does not compromise the effectiveness of any subsequent layer. In a preferred embodiment, the control processor **(50)** periodically self-tests layers L1 and L2 at session startup by injecting synthetic boundary conditions and verifying correct response; layers L3, L4, and L5 are verified by scheduled operator inspection at intervals not exceeding thirty (30) days.

9. Measurement Extraction Pipeline (FIG. 8)

[0078] FIG. 8 depicts the measurement extraction pipeline that transforms raw synchronized sensor streams into a set of clinically-meaningful measurement variables and a composite injury-risk score. The pipeline comprises a sensor-fusion module **(60)** and a risk-scoring engine **(62)**, each embodied as software executing on the control processor **(50)**.

[0079] The sensor-fusion module **(60)** accepts the time-synchronized sensor streams (force, joint trajectory, motor and drum encoder positions, and optionally sEMG) and computes, for each session, a set of nine (9) primary measurement variables, designated V1 through V9 and defined as follows:

[0080] **V1 — Range of motion at reference force.** Joint angle θ attained when the measured cable tension first reaches a predetermined reference force (in a preferred embodiment, 15 lbf), reported separately for left and right limbs.

[0081] **V2 — End-range stiffness.** The slope, $dF/d\theta$, of the force-angle curve evaluated over the final ten percent (10%) of the attained range of motion, expressed in pounds-force per degree.

[0082] **V3 — Bilateral asymmetry index.** Absolute difference between left and right V1, expressed as a percentage of the greater side, as further described in connection with step **(106)** of FIG. 3.

[0083] **V4 — Tissue yielding rate.** The time constant of the reduction in measured force when held at constant commanded joint displacement, characterizing viscoelastic creep of the tissue under load.

[0084] **V5 — Compensation index.** A scalar aggregating the magnitudes of detected compensatory movements of the pelvis, contralateral limb, and trunk during the stretch, normalized by the primary joint displacement.

[0085] **V6 — Neuromuscular co-activation.** When the optional sEMG array **(48)** is present, the ratio of antagonist to agonist muscle activation integrated over the stretch hold; a high value indicates guarding or protective contraction that limits passive range of motion.

[0086] **V7 — Session-over-session trend.** The slope of V1 across the last n sessions (preferably n=8), indicating whether tissue extensibility is improving, stable, or regressing.

[0087] **V8 — Asymmetry persistence.** The number of consecutive recent sessions in which V3 has exceeded the asymmetry threshold of step **(106)**.

[0088] **V9 — Adherence score.** The ratio of completed to scheduled sessions over a rolling window, used to attenuate the weight accorded to longitudinal trends when insufficient sessions are available.

[0089] The risk-scoring engine **(62)** computes a composite injury-risk score R as a weighted non-linear combination of variables V1 through V9, the weights being calibrated against a reference population dataset and revised, by scheduled software update, as additional longitudinal data are accumulated. In a preferred embodiment, R takes values in a normalized range of zero (0) to one hundred (100), with higher values indicating greater short-term injury risk. The risk score is displayed in the operator interface of FIG. 6 and written to the session record of step **(110)** of FIG. 3.

10. Multi-Pattern Reconfigurable Platform (FIG. 9)

[0090] FIG. 9 depicts the geometry by which the apparatus supports a plurality of distinct stretch patterns on a single reconfigurable platform, without requiring tool-assisted modification. The platform comprises the support frame **(26)**, a first pulley station **(P1)** at a fixed reference position, and a second pulley station **(P2)** translatable along a linear track **(200)** mounted on the frame and lockable by a toolless clamp **(202)** at any of a plurality of discrete positions spaced by not more than five centimeters (5 cm).

[0091] In a first configuration (designated V1 patterns), the cable is routed through pulley station **(P1)** alone. In this configuration, the apparatus supports at least four (4) distinct stretch patterns comprising (i) a supine hamstring pattern, (ii) an adductor pattern, (iii) a hip-flexor pattern, and (iv) an ankle dorsiflexion pattern, each selected by a subject position on a padded platform and by a corresponding pattern selection on the touchscreen **(22)**.

[0092] In a second configuration (designated V2 patterns), the cable is routed from the spool **(14)**, over pulley station **(P1)**, and thence through the translatable pulley station **(P2)** to the cuff **(18)**. In this configuration, the apparatus supports at least three (3) additional stretch patterns comprising (v) a shoulder capsular pattern, (vi) a thoracic rotation pattern, and (vii) a seated spinal extension pattern. The translatable pulley station **(P2)**, together with the fixed station **(P1)**, defines a line of action of cable tension that can be configured to address the particular joint under assessment.

[0093] The platform therefore achieves, in a single apparatus of a footprint not exceeding four (4) square meters, seven (7) or more distinct stretch patterns that, in prior art assisted-stretching devices, would require a plurality of separate machines. The configuration for each pattern is selected by the operator via the touchscreen **(22)**, which thereupon displays graphical instructions for pulley repositioning, cable routing, cuff placement, and subject positioning.

11. PID Force-Compliance Control Loop (FIG. 10)

[0094] FIG. 10 depicts the closed-loop force-compliance control law implemented by the real-time control layer of the control processor **(50)**. The loop operates at a sampling rate of not less than one hundred iterations per second (100 Hz) and maintains the measured cable tension F_m at a commanded set-point F_* while preserving a compliance response that yields immediately upon detection of a compensation event, as described in connection with FIG. 11.

[0095] At each iteration k, the control processor receives the measured cable tension from the load cell **(16)** and the current compensation signal $c[k]$ from the vision-based compensation detector of FIG. 11. The commanded set-point is adjusted in accordance with an adaptive law:

$$F_*[k] = F_{target} - g(c[k])$$

wherein F_{target} is the prescribed reference force and $g(\cdot)$ is a monotonically non-decreasing reduction function bounded on the interval $[0, F_{\mathrm{target}}]$.

[0096] The instantaneous error $e[k] = F_*[k] - F_m[k]$ is processed by a proportional-integral-derivative compensator having parameters K_p, K_i, and K_d. In a preferred embodiment, $K_p = 2.4$, $K_i = 0.8$ per second, and $K_d = 0.15$ second. The compensator output is clipped to a global maximum torque corresponding to the software force ceiling (layer L1 of FIG. 7), and the integrator is subject to anti-windup clamping whenever the output saturates.

[0097] The compensator output is transmitted as a torque set-point to the FOC motor controller **(30)** of FIG. 4, which enforces the set-point at the motor **(10)**. The resulting cable tension is measured by the load cell **(16)** and returned as $F_m[k+1]$, closing the loop. The loop bandwidth is selected such that a step change in F_* is tracked within two hundred milliseconds (200 ms) with less than ten percent (10%) overshoot.

[0098] In combination with the adaptive set-point law of paragraph [0095], the loop thereby exhibits the novel behavior that, upon detection of compensation, the commanded force is reduced in real time, the PID loop then tracks the reduced set-point, and the subject experiences an immediate and proportionate yielding of cable tension. This behavior is unattainable by simple position-controlled or constant-torque devices of the prior art.

12. Vision-Based Compensation Detection (FIG. 11)

[0099] FIG. 11 depicts the compensation detection algorithm executed by the vision and sensor-fusion layer of the control processor **(50)**. The algorithm identifies, in real time, compensatory motion by the subject, the onset of such motion being indicative that the subject has reached the passive limit of the targeted tissue and is recruiting secondary body segments to yield additional apparent range of motion. Continued application of force beyond this limit is a principal cause of injury in manual assisted-stretching practice.

[0100] The algorithm receives from the vision processing module **(42)** a time series of skeletal joint positions at not less than thirty frames per second (30 fps). At each frame t, the algorithm computes:

[0101] (i) a primary joint angle time series $\theta_{\text{primary}}(t)$, defined in accordance with the selected stretch pattern (for a hamstring pattern, the hip-flexion angle as described in paragraph [0066]); and

[0102] (ii) a compensation-segment displacement vector **(220)** $\mathbf{d}_{\text{comp}}(t)$ comprising, in a preferred embodiment, (a) pelvic tilt angle about the medial-lateral axis, (b) contralateral hip abduction angle, (c) lumbar flexion angle, and (d) trunk rotation angle, each referenced to the subject’s configuration at the start of the stretch hold.

[0103] A compensation signal generator **(222)** computes the scalar compensation signal $c(t)$ as a non-negative weighted norm of the compensation-segment displacement vector, in a preferred embodiment:

$$c(t) = \sqrt{\left(\sum_i w_i \cdot (d_i(t) - d_{i,0})^2\right)}$$

wherein w_i are pattern-specific weights calibrated such that $c(t)$ takes the value zero under pure-primary motion and increases monotonically with the magnitude of compensation. The signal is smoothed by a first-order low-pass filter with cutoff selected to attenuate camera noise without appreciable delay (preferably 5 Hz).

[0104] A force reduction mapper **(224)** transforms the compensation signal $c(t)$ into the reduction quantity $g(c)$ used by the adaptive set-point law of paragraph [0095]. In a preferred embodiment, $g(c)$ is zero for c below a dead-band threshold c_0, increases linearly with a slope m for c in the interval $(c_0, c_0 + F_{\text{target}}/m)$, and saturates at F_{target} thereafter. The dead-band threshold c_0 is chosen to reject postural micro-movements that are not indicative of true compensation, and the slope m is chosen to produce substantially full force relief within two hundred milliseconds (200 ms) of the onset of a clinically significant compensation event.

[0105] When the optional sEMG array **(48)** is present, the co-activation variable V6 of paragraph [0085] is used as an additional input to the compensation signal generator **(222)**, whereby antagonistic muscle guarding is detected as a form of compensation even in the absence of external kinematic deviation. In such embodiments, a single multi-modal compensation signal is produced by weighted fusion of the kinematic and electromyographic contributions.

[0106] The compensation detection of FIG. 11, acting through the adaptive set-point law of FIG. 10, produces the characteristic "assist-up, yield-down" behavior that distinguishes the apparatus from prior-art passive cable machines, constant-torque winches, and stiffness-mat systems. In particular, the apparatus applies increasing force to carry the targeted joint through its true passive range of motion and immediately yields when the subject begins to recruit secondary segments, thereby protecting the targeted tissue from supra-physiologic loading.

WHAT IS CLAIMED IS

1. A method for force-controlled assisted stretching of a human subject, the method comprising: providing an apparatus comprising a motor-driven cable having a distal terminus adapted to couple to a limb of the subject, a load cell configured to measure cable tension, a depth-sensing camera configured to observe the subject, and a control processor; by the control processor, commanding a torque set-point to the motor such that the cable applies a commanded force F_{target} to the limb; by the depth-sensing camera and the control processor, computing in real time a compensation signal $c(t)$ representative of compensatory motion of one or more body segments of the subject other than the limb; adjusting the commanded force in real time in accordance with an adaptive set-point law $F_*(t) = F_{\text{target}} - g(c(t))$, wherein $g(\cdot)$ is a monotonically non-decreasing function; and closing a force-feedback control loop sampled at not less than one hundred hertz (100 Hz) that drives the measured cable tension toward the adjusted commanded force.

2. The method of claim 1, wherein $g(\cdot)$ comprises a dead-band interval in which $g(c)$ is zero, a linear interval in which $g(c)$ increases monotonically with c, and a saturation interval in which $g(c)$ is held equal to F_{target}.

3. The method of claim 1, wherein the compensation signal $c(t)$ is computed as a weighted norm of displacements, relative to a configuration measured at the start of the stretch hold, of at least two of: pelvic tilt, contralateral hip abduction, lumbar flexion, and trunk rotation.

4. The method of claim 1, wherein the force-feedback control loop comprises a proportional-integral-derivative compensator with anti-windup clamping, the output of which is bounded by a software force ceiling less than a mechanical slip-release torque.

5. The method of claim 1, further comprising: prior to adjusting the commanded force, measuring a left-limb baseline and a right-limb baseline of the subject at a common reference force, and computing a bilateral asymmetry index as a percentage difference between the left and right baselines.

6. The method of claim 5, further comprising triggering an injury-risk flag and modifying a subsequent stretch protocol when the bilateral asymmetry index exceeds a predetermined threshold.

7. The method of claim 1, further comprising computing a plurality of measurement variables comprising at least: a range of motion at a reference force, an end-range stiffness, a tissue yielding rate, a compensation index, and a session-over-session trend, and logging the variables to a non-transitory data store.

8. The method of claim 7, further comprising computing a composite injury-risk score R as a weighted non-linear combination of the measurement variables, and outputting the composite injury-risk score to an operator-facing display and to a remote athlete-management system over an authenticated encrypted transport.

9. The method of claim 1, further comprising receiving a signal from a surface electromyography array applied to the subject, computing an antagonist-to-agonist co-activation ratio from the signal, and incorporating the co-activation ratio as an additional input to the compensation signal $c(t)$.

10. The method of claim 1, wherein the force-feedback control loop tracks a step change in the commanded force within two hundred milliseconds (200 ms) with less than ten percent (10%) overshoot, and wherein a clinically significant increase in $c(t)$ produces substantially full reduction of the commanded force within two hundred milliseconds (200 ms).

11. An apparatus for force-controlled assisted stretching of a human subject, the apparatus comprising: a support frame; a brushless direct-current motor mounted to the frame; a reduction gearbox coupled to an output shaft of the motor; a torque-limiting slip clutch coupled to an output of the reduction gearbox; a cable spool coupled to an output of the slip clutch; a synthetic ultra-high-molecular-weight polyethylene cable wound on the cable spool and having a distal end; an inline load cell disposed along the cable between the cable spool and the distal end, the load cell configured to measure cable tension at a sampling rate of not less than one hundred hertz (100 Hz); a quick-release coupling at the distal end of the cable, the quick-release coupling being hand-operable to disengage the distal end of the cable from a limb-engaging cuff in less than one second; a depth-sensing camera mounted to the frame and arranged to observe the subject; a hardwired emergency stop switch operatively coupled to cut electrical power to a motor power stage independent of software; and a control processor operatively coupled to the motor, the load cell, the depth-sensing camera, and the emergency stop switch, and programmed to execute the method of claim 1.

12. The apparatus of claim 11, wherein the slip clutch is pre-set to release at a through-torque corresponding to a cable tension not exceeding one hundred twenty percent (120%) of a maximum operational force of the apparatus.

13. The apparatus of claim 11, wherein the cable has a minimum breaking strength of not less than two thousand pounds-force (2,000 lbf), thereby providing a cable safety factor of not less than forty (40) times the maximum operational force.

14. The apparatus of claim 11, further comprising a field-oriented-control motor controller configured to sample motor-phase currents at not less than eight thousand hertz (8 kHz) and to enforce a commanded torque at the motor to within five percent (5%) over an operating range.

15. The apparatus of claim 11, further comprising a first rotary encoder coupled to a shaft of the motor and a second rotary encoder coupled to an output shaft of the slip clutch, wherein the control processor is programmed to compare positions of the first and second rotary encoders, after compensation for a ratio of the reduction gearbox, to detect slip of the slip clutch in real time.

16. The apparatus of claim 11, further comprising a first pulley station in a fixed position on the frame and a second pulley station translatable along a linear track on the frame and lockable by a toolless clamp, the first and second pulley stations cooperating to support a plurality of at least seven distinct stretch patterns on a single apparatus.

17. The apparatus of claim 11, wherein the control processor is further programmed to retain a session record in an encrypted non-transitory data store using a symmetric cipher of not less than 256-bit key length, such that absence of network connectivity does not impair session execution or data logging.

18. The apparatus of claim 11, comprising five independent safety layers, the five safety layers comprising: (i) a software maximum-force ceiling; (ii) a compensation-triggered compliance reduction implemented by the control processor; (iii) the slip clutch; (iv) the hardwired emergency stop switch; and (v) the quick-release coupling, wherein failure of any one safety layer does not compromise effectiveness of any other safety layer.

19. A system for longitudinal soft-tissue assessment and injury risk monitoring of an athletic population, the system comprising: a plurality of apparatuses each according to claim 11; a remote server in network communication with each of the plurality of apparatuses over an authenticated encrypted transport; and software instructions executable by the remote server to aggregate session records received from the plurality of apparatuses, compute for each enrolled subject a composite injury-risk score as a weighted non-linear combination of a range of motion at a reference force, an end-range stiffness, a bilateral asymmetry index, a compensation index, and a session-over-session trend, and to transmit the composite injury-risk score by application-programming-interface endpoint to at least one external athlete-management system.

20. The system of claim 19, wherein the software instructions are further executable to revise the weights of the composite injury-risk score, by scheduled update, as additional session records are accumulated across the plurality of apparatuses.

21. The system of claim 19, wherein the external athlete-management system is one of Smartabase, Kitman Labs, and Catapult Vector, and wherein the application-programming-interface endpoint is one of a REST endpoint and a GraphQL endpoint.

ABSTRACT OF THE DISCLOSURE

A cable-driven assisted-stretching apparatus, method, and system apply controlled, measured tension to a limb of a human subject and yield compliantly in real time upon detection of compensatory motion. A brushless motor, reduction gearbox, torque-limiting slip clutch, inline load cell, and quick-release cuff cooperate with a depth-sensing camera and a control processor running a closed-loop force controller at 100 Hz and a vision-based compensation detector at 30 Hz. An adaptive set-point law reduces commanded force as a monotonic function of a compensation signal computed from pelvic, contralateral hip, lumbar, and trunk displacement. A five-layer safety cascade (software ceiling, PID compliance, slip clutch, hardwired emergency stop, manual quick-release) protects the subject. Nine measurement variables and a composite injury-risk score are logged per session and exported to athlete-management systems, enabling bilateral longitudinal assessment on a single reconfigurable seven-pattern platform.

— End of Provisional Patent Application Specification —

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