	Darwing Hakobelude	Auxivo Liftsuit 1.0
Short Name	Darwing	Auxivo
Company	Daiya Industry Co.	Auxivo AG
Weight (kg)	0.8	0.9

TABLE I: Specifications of the soft exosuits used in the study. The table adapted from [1]

I. METHODS

A. Exosuit specifications

Table 1 and Figure 1 describes the two soft exosuits specifications. The Darwing exosuit has two textile elastic bands on each side that covers the upper interface to support the trunk and two on each side that covers the lower interface to support the lower limbs. Auxivo exosuit has two textile elastic bands on the upper back that connect to the thigh cuffs through adjustable straps to collectively support the upper back and thighs.

B. Prototype Design

Figure 1 shows the two soft passive exosuits with load cells attached. Miniature load cells were used for its compact size (S610 Miniature Load Cell, Strain Measurement Devices, Wallingford, CT, USA). These load cells were placed in series with each of the elastic bands to measure the stretch force directly upon elastic deformation. In Darwing, shown in Figure 1a, the load cells were placed only on the two elastic bands of the upper interface as the elastic bands of the lower interface could not be detached from the suit. One end of the load cell was drilled to the elastic band that is mobile and the other end of the cell was drilled to a stationary velcro extension as shown in the Figure 1b. Stretching of elastic band creates a tension in the load cell that leads to the part of the load cell connected to the elastic band (mobile part) to expand and the other part connected to the velcro extension to contract (stationary part). The resistive force generated due to tension is measured through load cells. In Auxivo, the load cells were drilled to the metal part of the elastic band on one end and to straps on the other as shown in Figure 1c. The force upon stretching of the elastic band was measured through load cells.

C. Load cell circuit setup

Load cells are simple and reliable for measuring tensile and compression loads. These are manufactured in various sizes to be widely used in different settings. Load cell acts as a transducer that converts physical quantities such as force and weight into a measurable electrical signal such as voltage [2]. Load cell is composed of strain gauges that are connected to each other in a bridge configuration. The bridge functions with a 5 volts(V) external DC power supply. When the load cell is subjected to external load or tension, the bridge undergoes instability and outputs a small voltage in response. Normally, the output voltage generated from the load cell is in the range of millivolts (mV). Hence, each load cell was coupled with an instrumentation amplifier. This study used a 24-bit ADC HX711 amplifier (Sparkfun, Niwot, CO, USA). This amplified the analog voltage inputs with a gain of 128 and converted those to corresponding digital values (signal conditioning). The default sampling rate of the amplifier was 10Hz which was up-sampled to 80Hz by altering an internal amplifier board connection. The manufacturer of HX711 amplifier had published an open-source script online [3] to interface the amplifier with Arduino Mega 2560 microcontroller (Arduino AG, Turin, Italy). The digital output from the amplifier was connected to the input digital ports of the Arduino. The Arduino was externally powered through laptop via USB cable. Libraries to recognize HX711 output ports were installed in the Arduino software and the open-source script was implemented. The script contained input parameters such as calibration factor and offset/zero factor that computed forces from the digital values. In general, force is calculated by the formula:

$$\text{Force (N)} = \frac{\text{Raw digital value} - \text{offset}}{\text{calibration factor}}$$

Raw digital value is the reading obtained at every instance(bits), offset(bits) is the initial baseline value that is read when the load cell is under zero stress and calibration factor(bits/N) is a constant value that is obtained through a separate load cell calibration experiment. The script contained inbuilt functions to carry out the above calculation and returned forces in Newtons as output.To copy and save the output values, an open-source terminal emulator called PuTTY was used. The output force values from Arduino were transferred through serial communication (COM port) to PuTTY terminal and the force values were stored in usual file formats.

1) Load cell calibration experiment: Before recording data from load cells, calibration of load cells is necessary for reliable measurements [4]. This is a one-time procedure to set the calibration factor unless the positions of load cells are altered. Known weights in kg or N were suspended from the elastic band creating a stretch. The calibration factor responsible for force calculation was scaled or adjusted until the reading matched the known force value. This was done for all load cells in both exosuits and were incorporated in the script accordingly.

The designed prototypes with calibrated load cells were evaluated through experiment trials with human subjects.

D. Experiment protocol

1) Participant information:

9 participants (height in cm: 173.8 ± 11.1, weight in kg: 73.4 ± 16.5, age in years : 23.5 ± 1.4) with no previous experience with exosuits and with no history of back injuries participated in the study. Besides the 9, one participant (height: 186cm, weight: 84kg, age: 70 years) from an industry also

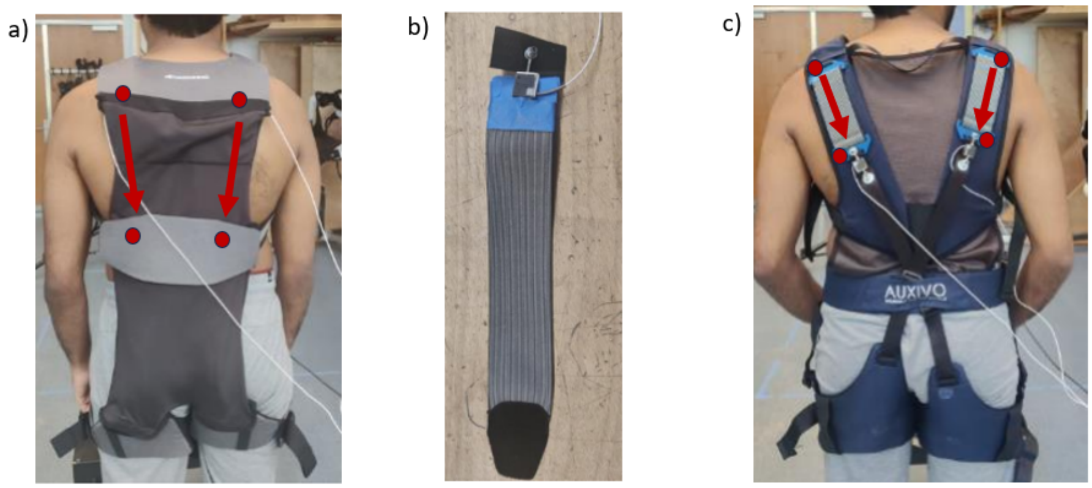

Fig. 1: a) Darwing exosuits with load cells attached to the elastic bands situated inside the exosuit. b) Load cell attached to one end of an isolated elastic band from the exosuit. c) Auxivo exosuit with 2 load cells attached to elastic bands on the outside. The red arrows in both exosuits indicate the line of action of stretch force and the red dots are the positions of markers at the anchoring points of the elastic bands on the exosuits

took part in the data collection. All participants provided informed consent. The Natural Sciences and Engineering Sciences Ethics committee of the University of Twente approved this experiment protocol (ref.number: 240424)

2) Apparatus:

For this study, data from the load cells, reflective markers (Qualisys Medical AB, Gothenburg, Sweden), ground reaction forces (1 AMTI force plate, MA, USA), wireless inertial measurement units (IMUs) (Xsens Technologies B.V., Enschede, Netherlands) and wireless surface EMG sensors from COMETA (Picolite EMG, Milan, Italy) were collected. 5 EMG sensors were placed on 3 bilateral dorsal muscles: Longissimus Thoracis pars Thoracis (LT-R,LT-L), Longissimus Thoracis pars Lumborum (LL-R,LL-L), and Right Iliocostalis (IL-R). 63 optical markers were placed on the participant. 56 full-body markers on bony landmarks and body segments and 7 on the each exosuit. 17 full-body IMU sensors were placed on the subject. Data from IMUs were visualized using the analyze software for trunk and knee joint angles during static hold trials. Marker data were sampled at 128 Hz, EMG data at 2048 Hz and load cell data at 80Hz. Manual synchronization of Arduino and Qualysis system was implemented to compare load cell, marker and EMG data at same time sequences.

3) Experiment procedure:

After placement of EMG sensors, IMUs and markers, subjects were asked to perform maximum voluntary contraction (MVC) trial to maximally activate the back muscles and IMU calibration. After this, exosuits were fit to correct user specifications and the tasks were performed with both

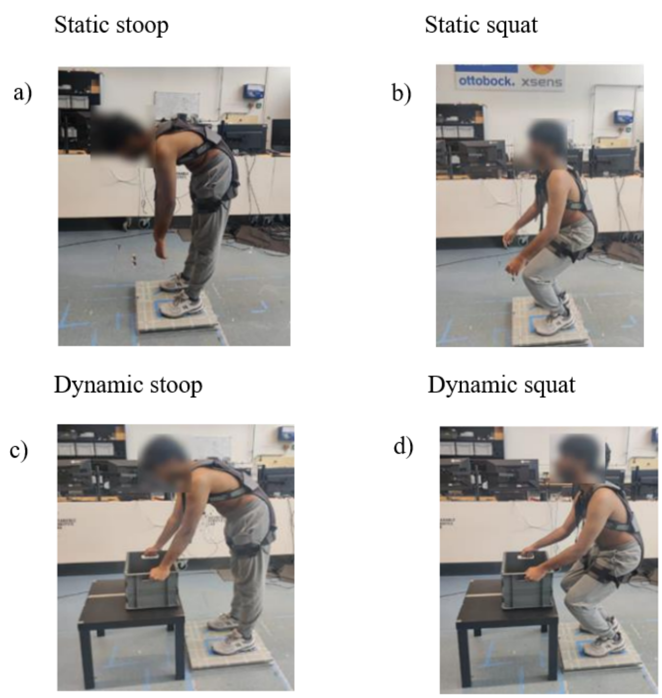

Fig. 2: a) Subject performing forward bend with minimal knee flexion b) Subject performing squat with minimal trunk flexion. c) Subject performing stoop lifting technique with a box d) Subject performing squat lifting technique with a box

exosuits. The tasks primarily involved two movements in the sagittal plane namely, stoop and squat that are often associated with industry-related tasks [5].

1) *Static hold trials:* Participants were asked to perform stoop at predefined trunk flexion angles of $40°$, $60°$ and $80°$, hold for 3 seconds and return to back erect posture. Similarly, participants were asked to perform squat at predefined knee flexion angles of $70°$, $90°$ and $110°$, hold for 3 seconds and return to back erect posture. The squat and stoop movements were repeated thrice each.

2) *Dynamic trials:* Participants were asked to perform stoop where they flexed their trunk to lift an empty box from a table placed in front of the them, returned to back erect posture and again flexed their trunk to place the box back on the table. Similarly, participants did squat by flexing their knee to lift an empty box from a table placed in front of the them, returned to back erect posture and again flexed their knee to place the box back on the table. Additionally, dynamic squat with 5kg weight and dynamic squat with roughly 50% assistance from the exosuit (loosening the straps to 50% disengagement of the suit) were performed. The squat and stoop lifting movements involved 5 repetitions each at 40 beats/min using metronome.

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