Evaluation of thermal properties and thermoregulatory impacts of lower back exosuit using thermal manikin

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Abstract

As exoskeletons and exosuits rapidly transition from laboratory to practice, the thermal discomfort posed by wearing the devices is emerging as a significant challenge towards their widespread adoption. We use a thermal manikin coupled with a thermoregulation model to evaluate the thermal properties and thermophysiological impacts of such devices. We measure thermal and evaporative resistances of summer and full clothing coupled with a legacy low-back supporting exosuit and its successor that features two design alterations to improve the user's thermal comfort. We quantify the decrease in evaporative resistance provided by substantial perforation of the back portion of the updated exosuit. The thermal manikin can replicate local skin temperature decrease associated with a release of a dual-mode thigh body attachment measured during a prior human trial. Using the thermal manikin coupled with a thermoregulation model, we simulate how the updated exosuit with several levels of assumed metabolic rate reduction impacts sweat rate, skin and core temperature changes during multiple work-rest cycles in a hot and humid climate. While a large metabolic rate reduction (>15%) is required to significantly slow the core temperature increase, even a minor metabolic rate reduction (5%) could provide a substantial reduction (20%) in the sweat rate (i.e. could reduce dehydration). Results suggest that thermal manikins with a thermoregulation model are an effective and efficient platform for comparing exosuit design features and for improving their thermal aspects. Our study highlights the comprehensive method and importance of considering thermal aspects when designing exosuits for occupational use.

Keywords: Exoskeleton, Exosuits, Human thermoregulation, Heat stress, Thermal comfort,

Highlights

- Thermal manikin is used to measure the thermal properties of exosuits
- Improved exosuit design reduces thermal and evaporative resistances
- Manikin in adaptive mode replicates prior limited human trial results with exosuits
- Exosuits could reduce heat stress during heavy work in hot conditions
- Even a minor reduction in metabolic rate could decreases sweat rate

1. Introduction

As exoskeletons and exosuits rapidly transition from laboratory to practice in clinics and industry (Ali, 2014), thermal discomfort posed by the use of the devices is emerging as a major challenge to their adoption and a common suggested area for improvement (Barrero, 2018; Benavides, 2020; Elstub et al., 2021; Liu et al., 2021; Omoniyi et al., 2020; Rykaczewski, 2022; Smets, 2019). An exoskeleton or an exosuit can be defined "as a wearable device that augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body" (ASTM F3323-19, 2019; Del Ferraro et al., 2020). Accordingly, the design of exoskeletons and exosuits has focused on biomechanical improvements resulting in many commercial devices that provide structural support and thereby reduce muscle fatigue and/or enhance a person's ability to do physical work (Bär et al., 2021; Del Ferraro et al., 2020; Hwang et al., 2021; Iranzo et al., 2020; Kermavnar et al., 2021; Voilqué et al., 2019; Zelik et al., 2022). Such devices have the potential to address immense biomechanical problems workers face due to excessive and repeated physical tasks in many industrial sectors (e.g., automotive (Spada et al., 2017), construction (Cho et al., 2018), agriculture (Omoniyi et al., 2020), retail (Marino, 2019), and steel (Yu et al., 2015) industries). In particular, over half of work-related health problems are related to musculoskeletal issues (Bär et al., 2021; Del Ferraro et al., 2020). Using exoskeletons could help lower the annual 19.4 million workplace injuries seen in the United States (Smith et al., 2005). However, in the push to optimize biomechanical aspects, the thermal impacts of the exoskeletons and exosuits have largely been neglected.

As feedback from industrial adopters (Barrero, 2018; Benavides, 2020) and recent research is showing (Elstub et al., 2021; Liu et al., 2021), wearing of exoskeletons or exosuits in certain environments can cause thermal discomfort and a negative user experience. Such impressions can slow the acceptance and widespread adoption of the devices in workplaces and clinics (Del Ferraro et al., 2020). Exoskeletons and exosuits can alter heat transfer between the human body and its surroundings in several ways (Rykaczewski, 2022), with the most apparent being thermal insulation and inhibition of sweat evaporation of skin areas covered by the device. This issue is the target of the first exosuit design alterations aiming at alleviating the thermal discomfort issue. Specifically, the Herowear Apex 2 Exosuit released in March of 2023 replaces the essentially impermeable back portion with a substantially perforated equivalent and features dual-mode thigh attachments that can be easily loosened and suspended from a belt when the device is not engaged (Elstub et al., 2021; Lamers and Zelik, 2021). The latter feature has been shown in a human trial (walking (1.3 to 1.6 met) and lifting (4.5 met) activities in air temperature of 22.7±0.5°C, relative humidity of 40.5±1.5%, and velocity of 0.15±0.05 m/s) to rapidly reduce local skin temperature by 2ºC to 4ºC and improve the thermal comfort of half of the participants (Elstub et al., 2021). A large response variability is an inherent trait of human trials, which can also be complex, time-consuming, and costly to conduct. These characteristics make a systematic comparison of exosuit design features aiming at improving thermal aspects using human trials cumbersome.

In this work, we demonstrate the use of a thermal manikin as a platform for systematically evaluating the thermal properties of exosuits and the thermoregulatory impacts of wearing such devices (i.e., skin and core temperature evolution). Thermal manikins are human-shaped instruments that measure surface temperature and heat flux, generate "metabolic" heat, and dispense sweat on their shell (Holmér, 2004; Parsons, 2014). These instruments are commonly used in the evaluation and development of casual and performance apparel (Al-Ajmi et al., 2008; Fan and Tsang, 2008; Parsons, 2014), protective garments for civil (e.g., firefighter (Mandal et al., 2017)) and military (Ducharme et al., 2004; Endrusick et al., 2005) applications, and accessories such as cooling wearables (Bendkowska et al., 2010; Bogerd et al., 2010; Gao et al., 2012; Jetté et al., 2004; Martinez-Albert et al., 2023; Xu and Gonzalez, 2011), helmets (Bogerd et al., 2011; Bogerd and Brühwiler, 2008; Pang et al., 2014), and sleeping bags (Huang, 2008).

We employ a sweating thermal manikin (see **Figures 1a** and **1b**) to measure the thermal and evaporative resistances of the legacy and updated Herowear Apex lower back supporting exosuits worn over summer and full clothing ensembles. Besides providing the only example of design alterations specifically targeting thermal aspects, we selected the exosuits that aim to aid with lifting because this motion is the most common source of work-related musculoskeletal disorders reported in the United States (Zelik et al., 2022). With the aid of three-dimensional topographic imaging of the manikin wearing the various exosuits and clothing ensembles, we discuss the physical mechanisms underlying the measured thermal and evaporative resistance values. We use the thermal manikin coupled with a thermoregulatory model to replicate prior human trial demonstrating the thermal performance of the dual-mode thigh body attachments (Elstub et al., 2021). We also use the manikin in this "adaptive mode" (the manikin's heating and sweating rates are controlled using a human thermoregulation model, see further description in Methods section 2.2.2) to quantify the impact of the exosuit on skin and core temperature evolution during representative work-rest cycles in a hot environment. For the latter, we evaluate the thermoregulatory impacts of several levels of the metabolic rate decrease attained by wearing exosuits (Del Ferraro et al., 2020; Liu et al., 2021) and discuss the potential for associated reduction in occupational heat strain and productivity loss caused by increasingly frequent hot weather conditions (Kjellstrom et al., 2016, 2009; Nybo et al., 2017; Vanos et al., 2021).

2. Materials and Methods

2.1 Materials

We selected two sets of commercially available clothing ensembles to evaluate the thermal properties of exosuits. Clothing ensemble A (**Figure 1c**) consists of garments described in ASTM F1291 (ASTM F1291-16, 2004) and ASTM F2370 (ASTM F2370-16, 2005) standards, including medium sized (or regular fit) plain weave protective Nomex shirts and pants (203 g/m^2, plain weave), underwear briefs (100% cotton jersey knit), a T-shirt (100% cotton jersey knit), calf-length athletic socks, and soft sole leather shoes. Clothing ensemble B (**Figure 1d**) consists of medium sized (or regular fit) summer garments, including single jersey briefs made of 100% cotton, a double-knitted short-sleeve T-shirt made of 65% polyester and 35% cotton, calf-length athletic socks made of 80% cotton, 8% acrylic, 7% nylon, and 5% elastic, and soft-soled shoes. To facilitate the dressing of the manikin, we made small cuts on one shoulder of the T-shirt and reattached the area using tape after dressing the manikin (see **Figure 1h**).

We tested the Apex 1 ("exo 1") and a pre-production version of Apex 2 ("exo 2") passive back-assist exosuits from HeroWear LLC (see **Figures 1e** and **1f**). Both devices use a set of elastic bands spanning back and thigh body attachment sites to reduce back muscle activity by 14% to 43% and muscle fatigue by 29% to 47% during bending and lifting tasks (Lamers et al., 2020; Lamers and Zelik, 2021). The Apex 2 exosuit features a perforated back panel with around half reduction in the surface area compared to the original Apex 1 model. It also has dual-mode thigh attachments that can be easily loosened and suspended from a belt when the device is disengaged (see **Figure 1h**). Both new features aim to improve the user's thermal comfort by facilitating the heat and mass transfer between the user's body and its surrounding. We measured the thermal properties of four exosuits and clothing ensembles (exo 1-clothing A, exo 1-clothing B, exo 2-clothing A, and exo 2-clothing B combinations, see examples in **Figures 1g** and **1h**).

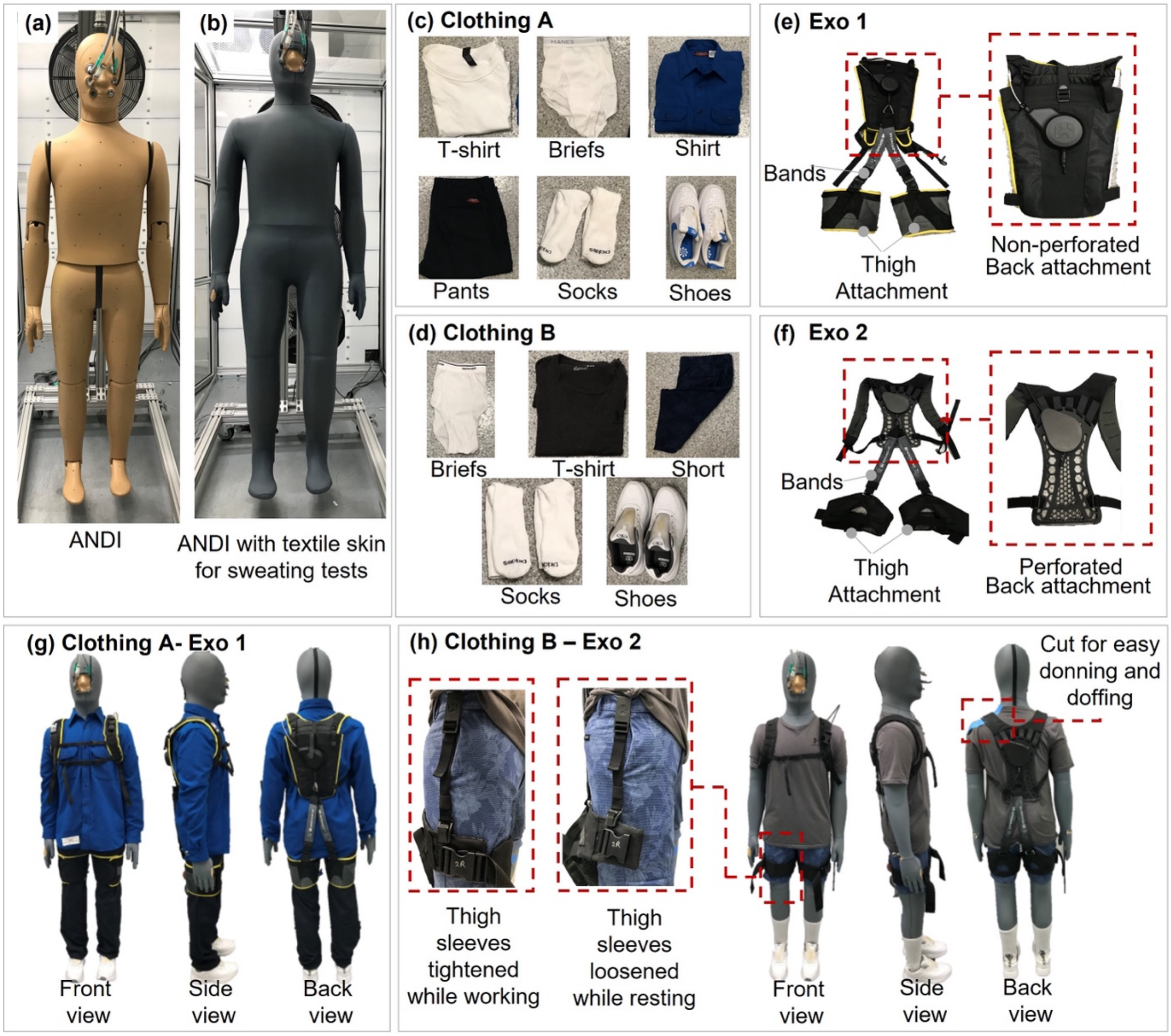

Figure 1. (a) Thermal manikin ANDI in the nude and (b) wearing textile skin to spread the sweat (water) uniformly over its surface; the clothing ensemble (c) "A" (full length) and (d) "B" (summer); exosuits (e) "1" (Apex 1: "Exo 1"), (f) "2" (Apex 2: "Exo 2"); and example of ANDI wearing (g) the Exo-1 and clothing ensemble A and (h) Exo 2 with clothing ensemble B.

2.2 Methods

2.2.1 Wind enclosure and climatic chamber

To ensure homogeneous airflow conditions with low turbulence, we conducted all measurements in a custom-built wind enclosure (1.15 m wide, 3.45 m long, and 2.21 m high, see **Figure 2**) located inside a fully sealed climatic chamber (2.75 m wide, 6 m long, and 3 m high chamber from BioCold located in Walton Center for Planetary Health on ASU Tempe campus). The wind enclosure is made of 15 mm extruded aluminum framing and polycarbonate panels (Faztek Industrial Solutions) that are sealed with silicone strips and expandable foam. The air is pulled across the enclosure by three 0.61 m (24") diameter fans (Xpower FD-630D) with continual velocity adjustment that are vertically mounted into a fan wall with fitting laser-cut acrylic panels. The wind enclosure entrance consists of a 6 cm thick polycarbonate honeycomb panel with 6 mm holes (Plascore), which induces predominantly horizontal flow with turbulence intensity (the ratio of root-mean-square of the turbulent velocity fluctuations and the mean velocity) below 6% at air speed of 0.4 $m \cdot s^{-1}$. We set the ambient conditions in the chamber according to the ASTM F 1291-04 and ASTM F 2370 guidelines for measuring the thermal and evaporative resistance of clothing.

For the thermal resistance measurement, we maintained the ambient temperature (T_a) at 23 ± 0.7°C, the relative humidity (RH) at 50 ± 3%, and the air speed (v_a) at 0.4 ± 0.05 $m \cdot s^{-1}$. We measured the evaporative resistance using isothermal settings, where the thermal manikin surface and ambient temperatures were 35 ± 0.7°C, the RH was 40 ± 3%, and the v_a was 0.4 ± 0.05 $m \cdot s^{-1}$. The ambient conditions in the climatic chamber and wind enclosure were monitored using a 3D sonic anemometer (CSAT3B from Campbell Scientific). The device was located 1.5 m upstream from the manikin and at 1.2 m height above the ground and caused negligible interference to air moving towards the manikin. The flow inside the wind enclosure is nearly uniform across its cross-section, which was confirmed by measuring wind speed at different locations (along the height and the width of the enclosure). Specifically, the mean air flow has a negligible variation throughout typical experimental time frame (1-2 hours) and varies at most by about 5% within the cross-section area occupied by the thermal manikin (e.g., ±0.1 m/s at 2 m/s for four measurement heights between 0.3 m to 1.7 m). The wind enclosure is also equipped with two temperature sensors and humidity sensors (Vaisala, Finland) to measure the ambient condition.

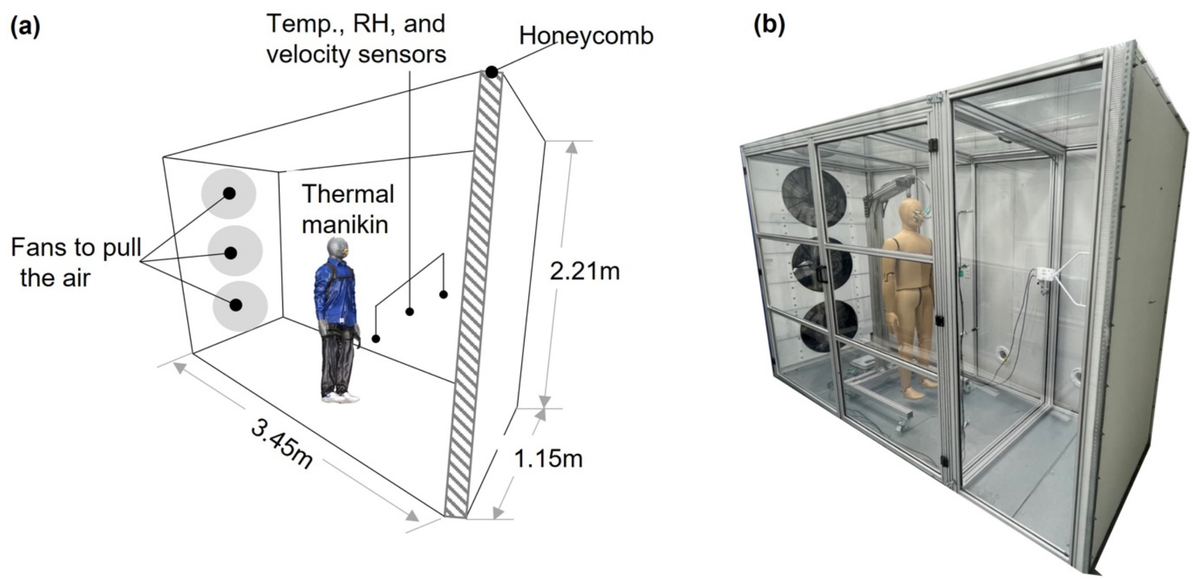

Figure 2. (a) Schematic diagram and (b) image of wind enclosure with the thermal manikin and sensor indicated.

2.2.2 Thermal manikin system

We conducted all measurements using ANDI sweating thermal manikin with 35 body segments with total surface area of 1.84 m^2 (Thermetrics LLC, USA) in either the constant shell ("skin") temperature or the adaptive mode (see **Figures 1a** and **1b**). The thermal and evaporative resistances of clothing ensembles with and without the exosuits are measured using the manikin's constant skin temperature mode (at 35 ± 0.7°C), in which the heating power necessary to maintain the skin temperature for given ambient conditions and clothing ensembles is adjusted. In the adaptive mode, the thermal manikin is coupled and controlled by a thermoregulation model, TAITherm (ThermoAnalytics, USA). In this mode, for each time step, the thermal manikin ("passive system") measures the skin temperature and heat flux for each surface segment and passes these values to the thermoregulation model ("active system"). Subsequently, based on metabolic heat (i.e., physical activity level) and the heat flux information used as boundary conditions, the model calculates updated core temperature and uses that along with the measured skin temperatures to set heater power (0 to 1000 $W \cdot m^{-2}$) and sweat rate (20 to 2000 $mL \cdot hr^{-1} m^{-2}$) for each segment for the next time step (see **Figure 3a**). Before starting the measurements in the adaptive mode, we initialized the manikin to achieve thermoneutral condition (preset skin temperature and sweat rate) as defined in UC Berkley thermal comfort model (Zhang, 2003). While running the measurement in adaptive mode, both systems ("passive system": thermal manikin and "active system": TAITherm thermoregulation model) interact during the experiments at every 9 seconds time steps to mimic the human thermophysiological response to given activity level (i.e., metabolic rate), ambient condition, and clothing/exosuit ensemble.

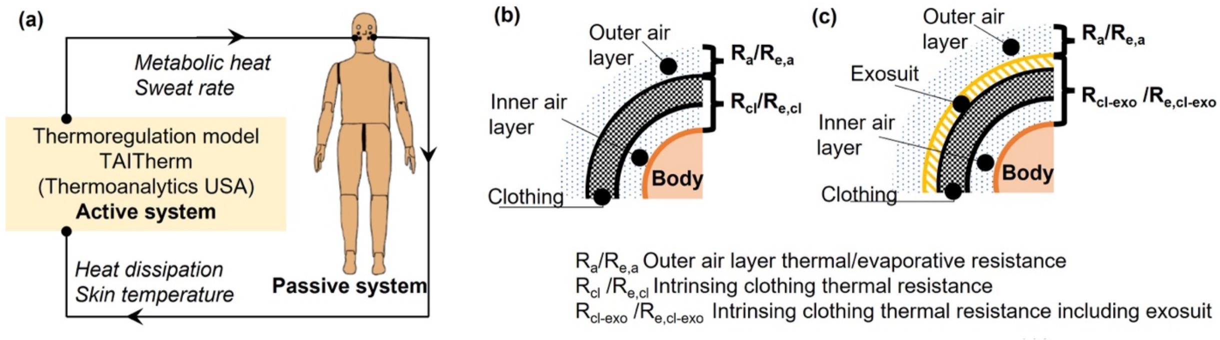

Figure 3. The schematic diagram of (a) the coupling between thermal manikin and thermoregulation model and cross-sectional view of (b) skin-clothing, and (c) skin-clothing-exosuit interface illustrating the location of inner and outer air gaps as well as indicating related resistances which added together form the total resistance.

2.2.3 Experimental Protocols and Calculations

Measuring the increase of the thermal and evaporative resistances related to wearing an exosuit requires separate measurements of the values for the shamelessly nude, clothed (A or B ensemble), and exo-suited up thermal manikin (one of the four clothing-exosuit combinations). The schematics in **Figures 3b** and **3c** show that these three experimental settings must be tested to measure outer (or boundary) air layer thermal/evaporative resistance $(R_a/R_{e,a})$, intrinsic clothing thermal/evaporative resistance $(R_{cl}/R_{e,cl})$, and intrinsic clothing thermal/evaporative resistance with exosuit $(R_{cl-exo}/R_{e,cl-exo})$. Firstly, we measured the thermal resistance (R_a) without any clothing on the nude thermal manikin. In the second step, we dressed the manikin in one of the clothing ensembles ("A" or "B") to measure the total thermal resistance $(R_{t,cl})$

incorporating both the boundary air layer and intrinsic resistances. Thereafter, we added the respective exosuit to quantify its effect on the total thermal resistance ($R_{t,cl}$). The thermal manikin provides the skin temperature of each of the 35 segments (T_i) and power required to maintain the skin temperature (q_i) for all three experimental settings (nude, clothing, and clothing with exosuits), which leads to total thermal resistance through the following equation:

$$R_{t,cl_j} = \frac{T_{skin_i} - T_a}{q_{i_j}} \tag{1}$$

Where i represents the individual body segment of the thermal manikin, j represents each of two cases, i.e., clothing and clothing with exosuit, $R_{t,cl}$ is the total thermal resistance of the clothing (units: $m^2 °C \cdot W^{-1}$), T_{skin} is the surface temperature of the manikin (units: °C), T_a is ambient air temperature (units: °C), q_{i_j} is the power required to maintain the constant temperature of the manikin surface (units: $W \cdot m^{-2}$).

Similarly, we measured the evaporative resistances for above mentioned three experimental settings. For these measurements, we dressed the manikin in a tight-fitted textile skin provided by Thermetrics, LLC to uniformly distribute water dispensed through internal tubing and surface pore network over the manikin's skin. Before starting the experiments, we saturated the textile skin with the liquid by enabling sweating through the sweating pores of the manikin and occasionally by applying the liquid externally. We neglect the effect of textile skin on evaporative resistance (R_{et,cl_j}) by assuming that the outer temperature of textile skin is same as the manikin skin surface (as experimental condition is isothermal and the thin fabric is tightly fitted with a low thermal resistance).

We performed these tests in isothermal conditions (see Section 2.2.1). Therefore, the power (q_{i_j}) required to maintain the constant skin temperature (T_i) is equal to latent heat transfer corresponding to the evaporation of sweat from the skin surface. Since there is no temperature gradient, the heat exchange is driven by the concentration gradient of water vapor between the skin and the surrounding. Accordingly, the total evaporative resistance can be calculated by the following equation:

$$R_{et,cl_j} = \frac{P_{skin_i} - P_a}{q_{i_j}} \quad (2)$$

As the skin was saturated the water vapor pressure at the skin surface is equal to the saturation pressure, for given temperature it can be obtained by the following equation (Lampinen, 2015):

$$P_{skin_i} = \frac{e^{77.354+0.0057\,T_{skin_i} - \left(\frac{7235}{T_{skin_i}}\right)}}{T_{skin_i}^{\ 8.2}} \quad (3)$$

Where $R_{et,cl}$ is evaporative resistance of the clothing (units: $m^2 Pa \cdot W^{-1}$), P_{skin} is water vapor pressure at the skin surface (units: Pa), and P_a is water vapor pressure of air (units: Pa). We repeated each test three times and reported uncertainty determined using the T-student distribution with two-sided 80% confidence interval (±1.886 standard deviation).

To understand the implications of wearing exosuits on human thermoregulatory response, we performed measurements using the thermal manikin's adaptive mode. The performance of the adaptive mode developed by the same manufacturer was previously validated for a wide range of metabolic rates (1 to 6.2 met), thermal environments (5°C to 47°C), and clothing insulations (semi-nude to protective clothing) (Blood and Burke, 2010; Burke et al., 2010; Hepokoski et al., 2015). To confirm our own system's performance, we conducted benchmarking against Psikuta et al. (2012) human trial and corresponding Fiala model simulation of 11 male subjects in semi-nude (0.1 clo) in moderate environment conditions (Ta: 30°C, RH: 30%) and for three metabolic rates (2.21 met (50 mins), 3.59 met (50 mins), and 0.98 met (30 mins)) (Haslam and Parsons, 1988; Psikuta et al., 2012). The manikin was initialized and stabilized for each experiment thermoneutral condition as described in Table S1 in Supplemental Material (Zhang, 2003). Once the thermoneutral condition was achieved, we started the thermoregulatory control mechanism of the manikin and input the respective experimental protocol into the control system. As shown in the Supplemental Material Figure S1, our results for the core temperature showed some underestimation in contrast to the original Fiala model but match within prior achieved uncertainties with those measured during the trial (Burke et al., 2009; Psikuta et al., 2012). Our mean skin temperature results matched well with the Fiala simulations but showed some deviation from the human measurements. The agreement with the simulations is unsurprising since the control software is based on a closely related thermoregulation model (Burke et al., 2009; Psikuta et al., 2012). The model and thermal manikin underpredict the skin temperature for cases involving high activity and sweat rates likely due to complexities in evaporative cooling of skin at measurement points in human subject study or inherent differences between the fabric "skin" and real human equivalent.

The two published studies on the thermophysiological impacts of exoskeletons only partially measured the human thermophysiological response (i.e., metabolic rate and mean skin temperature (Liu et al., 2021) or local temperature at lower thigh (Elstub et al., 2021)). Consequently, we could not conduct comprehensive adaptive mode experiment benchmarking (i.e., matching core and skin temperatures and sweat rates) against prior human trials involving exosuits. Instead, we replicated the Elstub et al. (2021) study focusing on the evolution of the local skin temperature under the thigh attachment of the Apex 2 exosuit prototype during an exercise protocol and following the opening of the attachment. We measured the thigh temperature using the manikin's sensor as well as using a T-type thermocouple (0.7 mm diameter, Minnesota Measurement Instruments) taped to the skin in the same location as in the human trial and data logging device (Stanford Research System, PTC10).

Lastly, we also used the manikin to explore the thermophysiological response of exosuit users during a hypothetical scenario in hot (T_a: 32.7°C) and humid (RH: 70%) indoor (v_a: 0.2 $m \cdot s^{-1}$) conditions with work (30 minutes) and rest (30 minutes) cycle continued for four hours. The hypothetical scenario was first simulated for clothing "B" only for "lifting activity" with a representative metabolic rate of 5.4 met (where a "met" is equal to 58 $W \cdot m^{-2}$) or 310 $W \cdot m^{-2}$ as scaled per surface body area (Liu et al., 2021). After that, the same exposure was simulated by adding exosuit and simulating several approximate levels of reduction in metabolic rates reported in the literature (5% (Del Ferraro et al., 2020), 15% (Baltrusch et al., 2020), and 30% (Liu et al., 2021)). The simulated hypothetical scenario can provide the details of workers' core and skin (mean and local) temperatures and sweat rates during prolonged heat exposure and provide insight on thermal comfort and heat strain. We repeated each of the thigh attachment loosening test three times and reported uncertainty determined using the T-student distribution with two-sided 80% confidence interval (±1.886 standard deviation). We observed only 0.1 to 0.2°C difference in core temperature and 0.2 to 0.5°C in mean skin temperature between the runs that can be explained by variation in clothing and exosuit fit as well as slight changes in the starting conditions. Consequently, we conducted only a single repetition of the extended 4 h experiments with varied metabolic rate.

2.2.4 3D Scanning and Post-processing

To generate three-dimensional (3D) models of ANDI's geometry, we used the Primsense Carmine 1.09 handheld 3D scanner (PrimeSense, Israel that Apple Inc. acquired). This device is equipped with a short-range 3D near-infrared scanner with a depth resolution of 1 mm (at 1 m away from the subject) and a 2D image resolution of 640x480 pixels. It also has a camera that receives light in the visible range, allowing for the pairing of both sensors to create a colored 3D model. The sensor was approximately 1 m away from ANDI for the duration of the scans, and a 1 m x 1 m x 2 m bounding box was chosen for the scanning volume. It is important to note that it was crucial to keep the camera orthogonal to the subject and to be as stable as possible at this 1 m distance to ensure smooth data collection. The scanner was positioned at 3 heights (shoulders, hips, ankles) to capture all body zones accurately. At each of these heights, the manikin was manually rotated 360° about the hanging stand attachment, as shown by the scan path in **Figure 4a.**

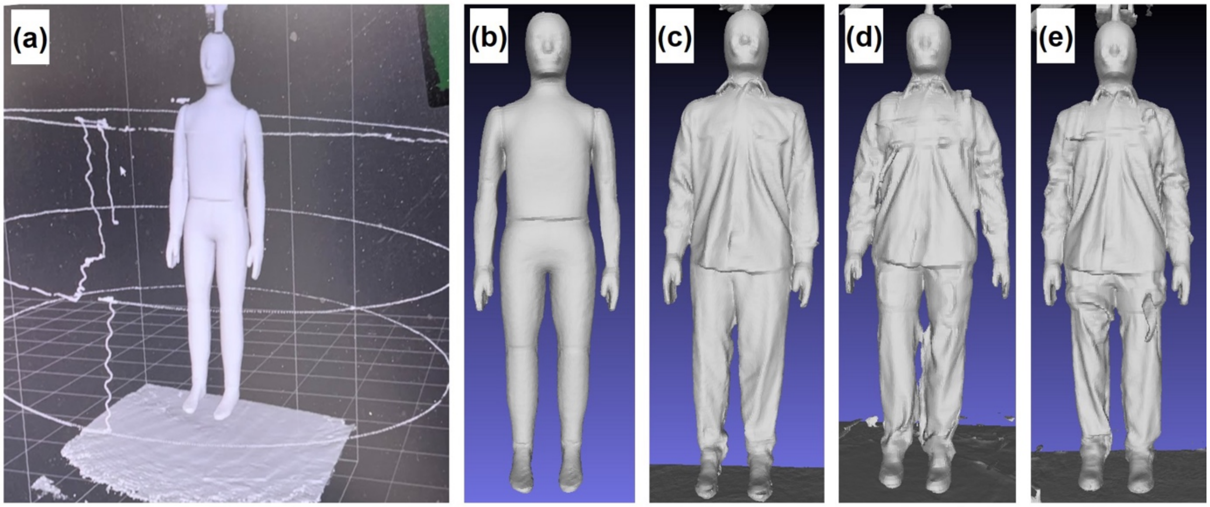

Figure 4. (a) 3D scanning paths at different heights; and 3D scan of the (b) nude manikin, (c) manikin dressed in Clothing A, (d) manikin dressed in clothing A and Exo 1, and (e) ANDI dressed in clothing A and Exo 2

After multiple passes the scanning software, *Skanect* (Occipital, USA), was able to filter out a large portion of the noise created by the manikin's surroundings. The software can map a mesh of a desired object in real-time, gaining higher accuracy each time a pass is complete. It does this by fusing each frame from the scan into a singular polygonal model. For this study, three passes around the manikin produced a mesh with sufficient quality, removing most of the unwanted geometry, such as the hanging stand and the surrounding walls of the wind tunnel. This entire process was performed for a nude ANDI, an ANDI with sweating skin, Clothing A, and Clothing A with Exo 1 and Exo 2.

The 3D models were then exported from Skanect to Autodesk Meshmixer (Autodesk, USA) where final refinements were made. First, all intersecting elements and duplicate nodes were deleted. Next all floating objects that were not part of the manikin's body were removed including the floor, hanging stand attachment and other scattered pieces. The fingers were simplified to be webbed mitten-like hands using the "brush inflation tool". Finally, using the "robust smooth" feature, any abnormalities that did not represent the true geometry were smoothened. Specifically, the armpit and groin regions needed attention during all scans. The surface area of each body zone and exosuits were also calculated for the data analysis.

3. Results and Discussion

3.1 Thermal Properties of the Exosuits

Based on 3D scanning analysis, we identified key body zones where the majority of surface area of the exosuits was distributed as the back and the thighs (83%); while the rest of the exoskeleton covers the chest. Therefore, out of 35 body zones of the thermal manikin, we reported local thermal and evaporative resistances of the chest (area weighted average of chest, stomach, shoulder, and underarms of the thermal manikin), the back (area weighted average of the upper and lower back of the thermal manikin), and the thigh (area weighted average of the upper thigh and lower thigh zones on the thermal manikin). We measured and compared the total thermal and evaporative resistances for three cases; (i) when manikin was donned with clothing A (standard clothing) or B (summer clothing), (ii) when manikin was donned with clothing A/B and Exo 1, and (iii) when manikin was donned with clothing A/B and Exo 2.

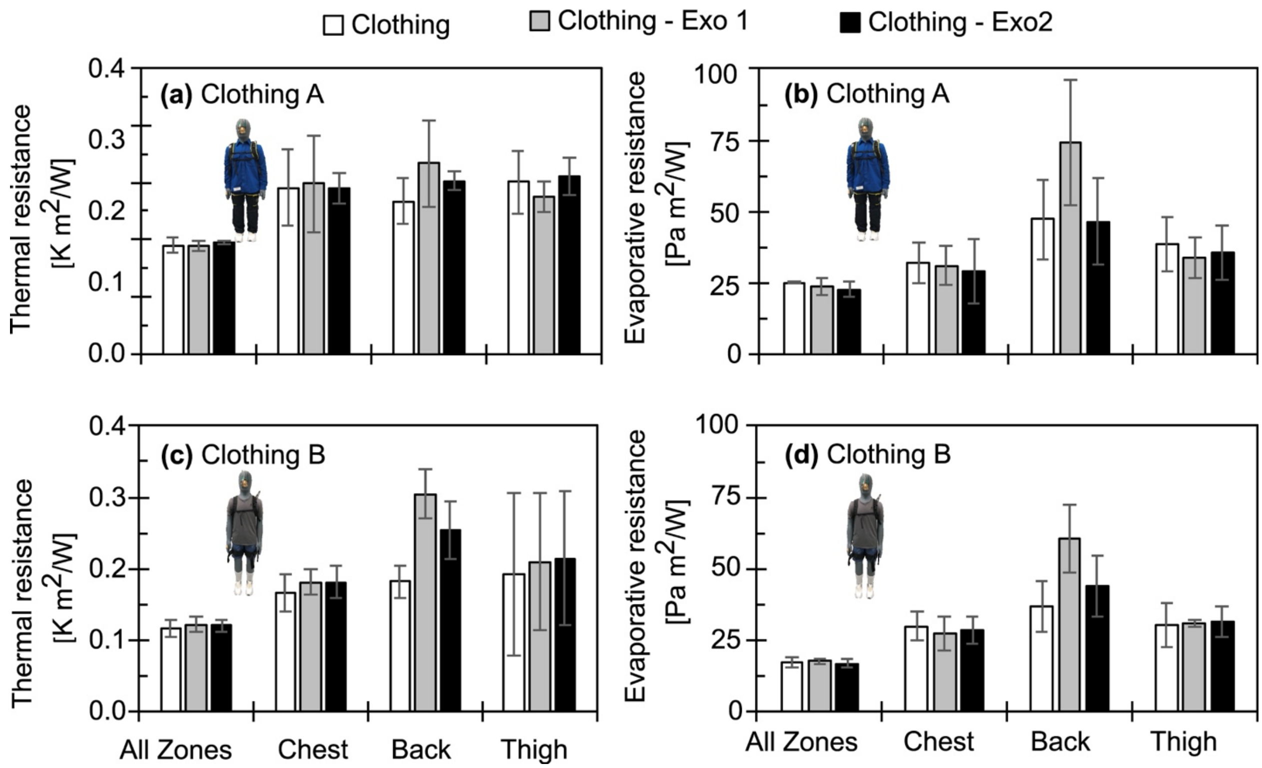

Figure 5. Total thermal and evaporative resistances of clothing A (a and b) and clothing B (**c** and d) with two different exosuits (Exo 1 and Exo 2). Uncertainty with 80% confidence interval (±1.886 standard deviation) is shown.

As depicted in **Figure 5**, the exosuits have a negligible effect on the total thermal and evaporative resistances for the chest, thigh, and entire body ("all zones"), as the average values are within the measurement uncertainty. We note that the devices only partially cover the chest and the thigh surface (47% of the thigh for Exo-1, 33% of the thigh for Exo-2, and 21% of the chest surface for both devices); therefore, these measurements are "diluted". In contrast, the exosuits cover most of the back area (74%), significantly affecting the corresponding thermal resistances. Specifically, the thermal resistance of the clothing at the back increases by 68% for Exo 1 and Clothing B, 25% for Exo 1 and Clothing A, 40% for Exo 2 and Clothing B, and 13% for Exo 2 and Clothing A. Similarly, wearing of the devices increases the evaporative resistances of the clothing at the back by 64% for Exo 1 Clothing B, 57% for Exo 1 and Clothing A, 19% for Exo 2 and Clothing B, but has a negligible impact (-1%) in case of for Exo 2 and clothing A.

Our measurements show that on the back of the manikin, Exo 2 performs better and is a relatively low obstruction to natural pathways of heat (thermal resistance) and mass (evaporative resistance) transfer between the manikin surface and the environment compared to Exo 1. The Exo 2 with the summer clothing (clothing B) has a thermal resistance of 0.25 $m^2°C·W^{-1}$, 40% higher than baseline Clothing B and equivalent to wearing an additional sweater (approx. 0.06 $m^2°C·W^{-1}$) (ISO 9920, 2009). This resistance is significantly lower than that for the Exo 1 of 0.31 $m^2°C·W^{-1}$, 68% higher than baseline Clothing B and equivalent to wearing additional winter down jacket/parka (approx. 0.10 $m^2°C·W^{-1}$) (ISO 9920, 2009).

We observed a similar trend as for the thermal resistances for the evaporative resistance measured on the back of the manikin. The evaporative resistance is a measure of the obstruction to the permeation of water vapor through fabric/clothing. A bare skin (no obstruction from clothing) has evaporative resistance of approximately 12.1 $m^2Pa·W^{-1}$ (ASTM F2370-16, 2005), whereas water vapor impermeable clothing can have evaporative resistance of greater than 1000 $m^2Pa·W^{-1}$ (e.g. fully encapsulated hazmat suit). The Exo 2 with the summer clothing (clothing B) has an evaporative resistance of 44 $m^2Pa·W^{-1}$, which is only 22% higher than 36 $m^2Pa·W^{-1}$ for baseline Clothing B. This resistance is significantly lower than that for the Exo 1 of 60 $m^2Pa·W^{-1}$, which is 67% higher than baseline Clothing B. The reduced resistances of the updated Exo-2 are primarily due to improved design at the back where the manufacturer applied perforated mesh with 50% less surface area as shown in **Figures 1e** and **1f**, providing the least heat and water vapor resistance.

3.2 Comparison of Thermal Manikin Simulated and Human Trial Thermo-physiological Responses To Thigh Body Attachment Release

The measurement of thermal and evaporative resistances of the exosuits provides the quantitative insight needed to compare the different thermal designs of the devices. However, the human thermophysiological response is essential to analyze the thermal comfort associated with wearing the exosuits. The Apex 2 exosuit includes a dual-mode thigh attachment that can be fully detached from the area and suspended from a waist belt when the exosuit is not used (e.g. during a short break). Elstub et al. showed that detaching the thigh sleeves during the rest period (or when assistive forces of exosuit are not needed) substantially decreased local skin temperature and improved thermal comfort reported by many subjects (Elstub et al., 2021). To test the utility of the thermal manikin in simulating transient human trials involving wearable devices, we subjected ANDI operating in the adaptive mode to the same exposure (T_{air} : 22.7±0.5°C, RH: 40.5±1.5%, v_{air}: 0.15±0.05 m/s) as Elstub et al.'s subjects that were walking on a treadmill. In particular, after the thermoneutral condition was reached, ANDI generated metabolic heat (and was actuated in walking motion) corresponding to walking at 1.3 $m \cdot s^{-1}$ (3 met or 175 $W \cdot m^{-2}$) for 5 minutes, walking at 1.6 $m \cdot s^{-1}$ (3.5 met or 204 $W \cdot m^{-2}$) for 5 minutes, and lifting 5 kg and 10 kg boxes and carrying them over 5 m (4.5 met or 260 $W \cdot m^{-2}$) for 15 minutes (ISO 8996, 2021). We tested the baseline condition with just summer clothing ensemble

(B) and the same clothing with Exo-1 that does not include the detaching interface and with Exo-2 that does. In the latter case, after completing the final trial step, we detached the thigh attachment from ANDI. To match the measurements taken during the human trial, we measured the thigh temperature using a thermocouple attached using tape (see **Figure 6a**). The plots in **Figures 6b** show that our skin temperature change measurements match those measured during the human trial. Furthermore, we were able to replicate the rapid skin temperature decrease by 2.5°C that followed the detachment of the thigh interface. In the Exo-1 case where attachments remained, the skin temperature at the thigh increased slightly (about 1°C) during our experiments, which aligns with the human subject study.

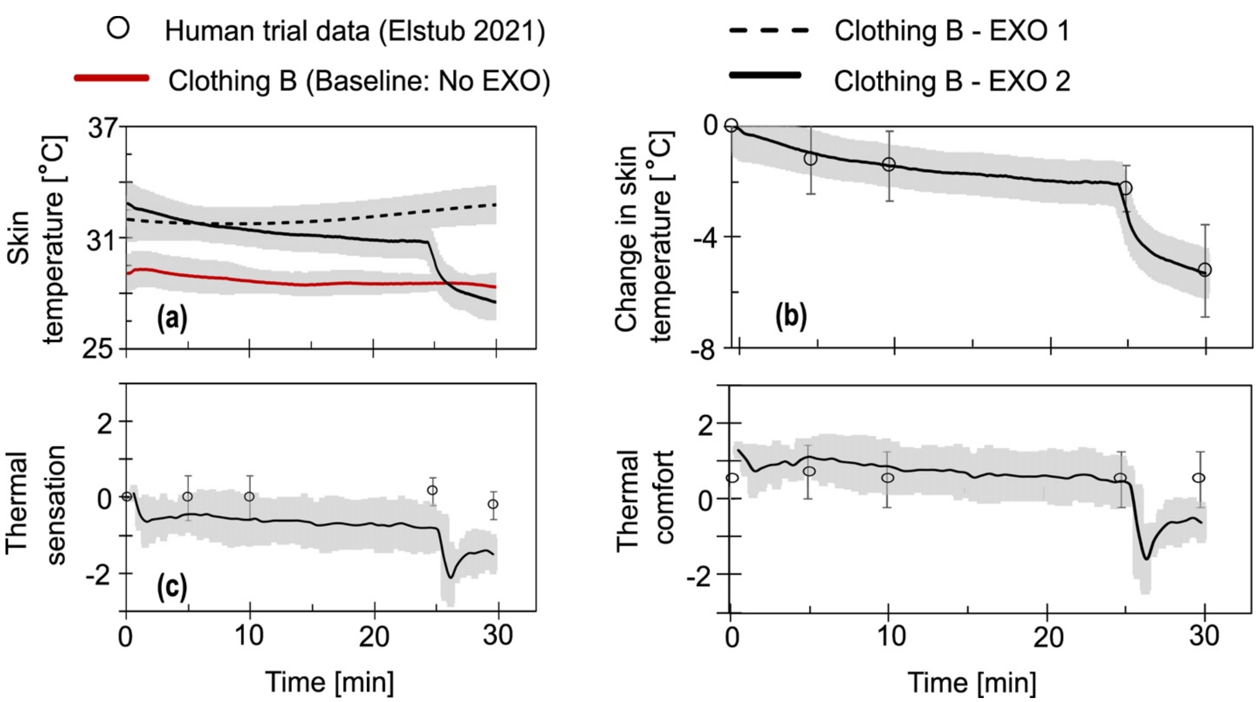

Figure 6. Comparison of measured (Human trial data: Elstub et al. 2021) and simulated (adaptive manikin) effect of wearing the two exosuit with summer clothing ensemble (B) on the **(a)** thigh skin temperature, **(b)** change in thigh skin temperature, **(c)** thermal

sensation (+3: hot, +2: warm, +1 slightly warm, 0: neutral, -1: slightly cool, -2: cool, and -3: cold), and **(d)** thermal comfort (+3: very comfortable, +2: comfortable, +1: slightly comfortable, 0: neutral, -1: slightly uncomfortable, -2: uncomfortable, and -3: very uncomfortable). For Exo-2, the thigh attachment was detached 25 minutes into the experiment.

The plots in **Figures 6c** and **6d** show that thermal comfort and thermal sensation obtained from subject questioning during human trial and those predicted using the thermal manikin simulation are within a reasonable agreement. The predicted thermal sensation is slightly lower than the one reported by subjects (between neutral and slightly cool vs. neutral) because the algorithm takes into account the temperature of the entire thigh, which can be lower than that just under the attachment (i.e., the one measured using the thermocouple). After the 25th minute when thigh attachments were loosened/detached, the evaporative and convective heat transfer increases rapidly leading to higher heat loss and skin temperature decrease. Accordingly, right after loosening of the attachment the thermal sensation algorithm predicts change from slightly cool to cool sensation while the thermal comfort algorithm predicts change from neutral to uncomfortable condition. Both of these recover to more neutral settings within a few minutes. As simulation provides data at a temporal resolution higher than human trials, the human thermal comfort and sensation data during this transition period is unavailable. At the end of exposure (30th minute) the simulation moderately underpredicts the human subjects' neutral vote on thermal sensation (neutral vs. slightly cool) and thermal comfort (neutral vs. slightly uncomfortable). These results suggest the applicability of the thermal manikin operating in the adaptive mode for analyzing the dynamic impacts of wearable devices such as exosuits on the human thermophysiological response. Furthermore, the performance of thermal manikin in adaptive mode was previously evaluated under wide range of conditions (metabolic rates/activity level, thermal environment, and clothing ensembles), proving that the system can adequately predict the human thermophysiological response under complex heat exposure (Blood and Burke, 2010; Burke et al., 2010; Hepokoski et al., 2015). Next, we demonstrate a significant advantage of the adaptive mode manikin over human trials: simulating of extended human exposure to a harsh thermal environment that, in some of the cases, could not be ethically conducted with real subjects.

3.3 The Thermoregulatory Impacts of Wearing Exosuits During Intensive Work in Hot and Humid Environment

Liu et al. (Liu et al., 2021) recently measured the human thermal responses (mean skin temperature and metabolic rate) and thermal sensations of participants wearing a lower-back supporting exoskeleton in cold (10°C, 50% relative humidity, <0.1 $m \cdot s^{-1}$ air flow) and in temperate (25°C, 50% relative humidity, <0.1 $m \cdot s^{-1}$ air speed) environments. After an adaptation period, the subjects were asked to lift and lower a 10 kg box by 75 cm continuously for 20 minutes. In cold conditions, wearing the exoskeleton substantially reduced the metabolic rate and was also perceived as thermally comfortable (i.e., having more thermal insulation in a cold environment is desirable). However, in temperate conditions, despite the substantial metabolic rate reduction (from an average of 313 $W \cdot m^{-2}$ to 225 $W \cdot m^{-2}$), users experienced deterioration of various thermal comfort metrics while wearing the exoskeleton. Irrelevant of the environment, the lifting period was too short to cause a measurable increase in the mean skin temperature. Thus, so far, the impacts of wearing an exosuit on users' health (Bär et al., 2021; Del Ferraro et al., 2020) have not yet been quantified for long-duration work in hot environments.

Wearing an exosuit might exacerbate the thermoregulatory impacts of hot environments by locally obstructing natural pathways of heat and mass transfer. However, simultaneously, the device might decrease thermal stress by reducing the metabolic rate required for a work task. It is worth noting that wearing of protective equipment/clothing can often have the opposite effect. In particular, protective clothing commonly worn in industrial and military settings can increase the metabolic rate due to added weight and restriction of movement by the extra layers (Dorman and Havenith, 2005, 2009; Renberg et al., 2020). To quantify the combined effects of these opposing exosuit impacts, we used the thermal manikin to simulate human thermal response to a long period (4 hours) of heavy work in a hot (32.7°C) and humid (70% RH) indoor environment (0.2 $m \cdot s^{-1}$ air speed and mean radiant temperature assumed to be equal to air temperature). Without solar radiation, these conditions are equivalent to wet bulb globe temperature (WBGT (Budd, 2008; Grundstein et al., 2015)) calculated using OSHA Outdoor WBGT calculator (Occupational Safety and Health Administration, 2023)) of 29.4°C (85 F). According to the United States military guidelines, this value of WBGT is within the "yellow heat category" and for heavy work requires 30-minute work and 30-minute rest cycle (USDAAF, 2003). Heavy work is specified as 600 W (USDAAF, 2003) or range of 440 to 704 W (Almario, 2019) which for 50th percentile western male with surface area of about 1.9 m^2 (Rykaczewski et al., 2022; Viswanathan et al., 2023) corresponds to 315 W·m^{-2} (5.44 met) or range of 370 W·m^{-2} (6.4 met) to 230 W·m^{-2} (4 met). We also consider the reduction in metabolic rate due to the assistive force of exosuits. The reduction in muscle fatigue and metabolic rate depends on the type of activity and forces/support provided by exosuits and varies between 5% to 30% (Baltrusch et al., 2020; Del Ferraro et al., 2020; Liu et al., 2021). Therefore, we simulated metabolic rate reduction of 5%, 15%, and 30% while wearing the Exo-2 suit. For the baseline case without the exosuit and associated metabolic rate reduction, we used the 5.4 met value reported by Liu et al. 2021 for continual lifting.

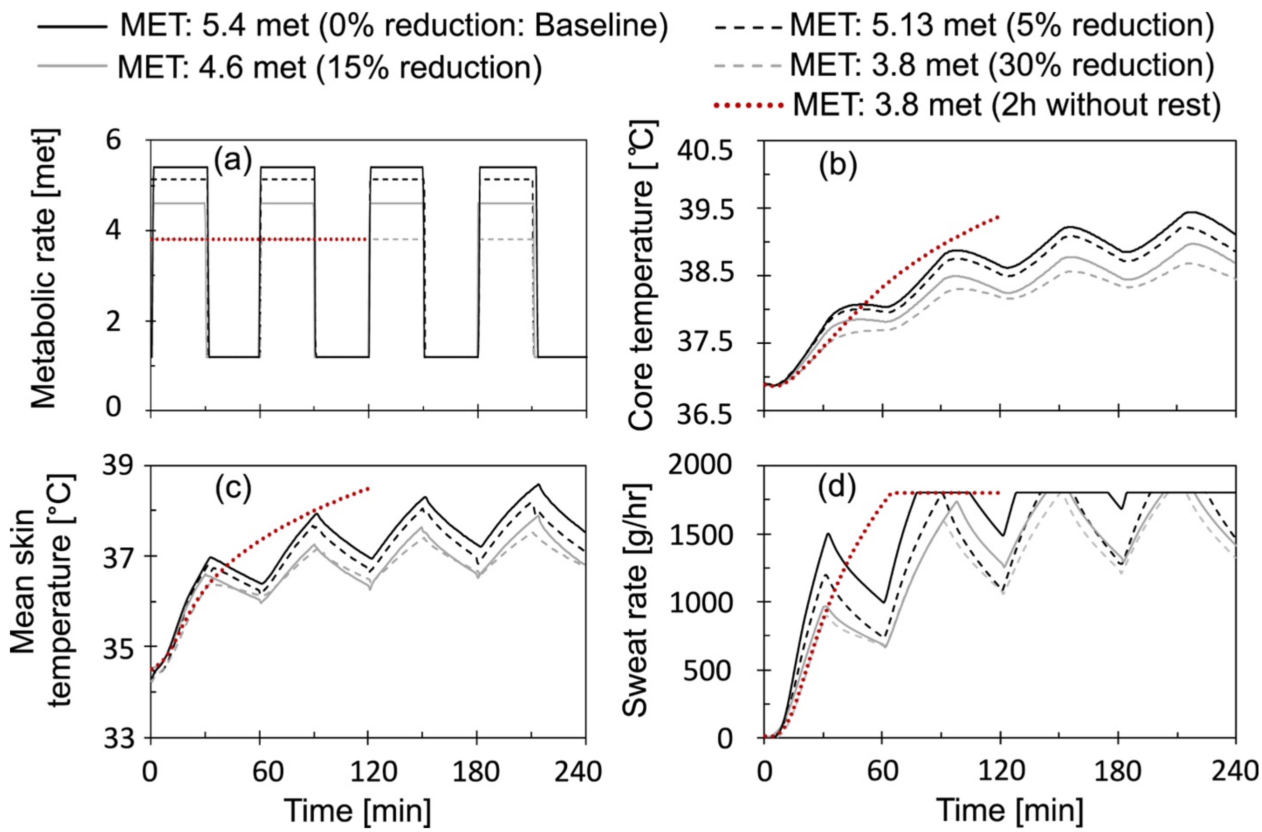

Figure 7. Thermoregulatory response of the thermal manikin performing heavy work on a 30-minute work-rest cycle in hot and humid conditions without (baseline condition with no metabolic rate reduction) and with the exosuit (Exo-2 and Clothing B): The temporal

evolution of the **(a)** metabolic rate, **(b)** core temperature, **(c)** mean skin temperature, and **(d)** sweat rate with a 5%, 15%, and 30% metabolic rate reduction associated with exosuit use.

The results in **Figure 7a-c** show that the heat strain caused by heavy work in hot and humid environments can be substantially decreased if an exosuit reduces the user's metabolic rate. In the baseline case without exosuit and metabolic rate of 5.4 met the core temperature, mean skin temperature, and sweat rate increased rapidly. Concerningly, in just the first 39 minutes of working, the core temperature in the baseline case increases over 1.2°C from 36.8°C to 38°C, which is when heat illness/exhaustion onset can occur (Jardine, 2007). In terms of core and mean skin temperatures increase during the first 30-minute work period, wearing an exosuit that reduces the metabolic rate by 5% has negligible impacts compared to the baseline case. During the subsequent rest and work cycles, the 5% reduction in metabolic rate provides a minor decrease of 0.1 to 0.2°C in these parameters. However, despite the first rest period, during the second work stage, the core temperature rapidly exceeds the 38°C concern threshold in both cases (baseline and exosuit with 5% metabolic rate reduction). This measurement implies that for safety reasons, a longer rest period or cooler conditions in the rest area should be implemented in these hot and humid conditions with very heavy work intensity.

In contrast to the negligible impacts of the devices providing 5% metabolic rate reduction, wearing exosuits that reduce the metabolic rate by 15% or 30% substantially decreases the rate of increase of the core and mean skin temperatures and prevents reaching the core temperature point of concern of 38°C within the first work period. Specifically, after 30 minutes of heavy work in hot and humid conditions, a user wearing the exosuits that provide the 15% and 30% metabolic rate reduction would experience a core temperature increase of 0.9°C to 37.7°C and of 0.7°C to 37.5°C, respectively. Furthermore, the core temperature of a user wearing the exosuit that provides a 30% metabolic rate reduction does not reach 38°C until the end of the second work period. Thus, exosuits providing 15% or more metabolic rate reduction should be highly beneficial in reducing core temperature increase in hot and humid conditions. In addition, **Figure 7d** shows that such devices could substantially reduce the user's sweat rate. For example, at the end of the first work period wearing such devices should reduce the sweat rate by 40% (from about 1500 $g \cdot h^{-1}$ to 900 $g \cdot h^{-1}$). Even wearing the device that reduces the metabolic rate by 5% (and has negligible impacts on body temperatures), reduces the sweat rate by 20% (from 1500 $g \cdot h^{-1}$ to 1200 $g \cdot h^{-1}$). Since dehydration is one of the compounding mechanisms driving different physiological pathways of human heat strain (Ebi et al., 2021), a substantial reduction in sweat rate could be an important health benefit of exosuit use.

Besides health benefits associated with reduced thermal strain, exosuits that significantly reduce the metabolic rate might also enable an increase in the duration of the continuous working period. In particular, the ~30% reduction in the metabolic rate from 5.4 met to 3.8 met theoretically decreases the work intensity level from "heavy" to "moderate", which removes any requirements of taking breaks during working in "yellow" WBGT conditions (USDAAF, 2003). Our simulations show that the 30% reduction in metabolic rate prevents the core temperature from reaching 38°C for nearly an hour of continuous work. However, continual work afterward causes the core temperature to increase beyond this threshold of concern for heat illness and also leads to sweating continuously at an extremely high rate. Consequently, exosuits have a significant potential to reduce the thermal strain associated with heavy work in hot environments (reduce core temperature and sweat rate) and could increase safe working for continual work (but with limits, e.g., from 30 minutes to 60 minutes but not beyond). It is essential to highlight that the reduction in metabolic rate will depend highly on the individual and specific work tasks. Thus, to safely extend a work period, the exosuits should be used along with wearable sensors that monitor the user's physiology (heart rate, temperatures, sweat rate etc. (Runkle et al., 2019)).

3.4 Limitations

One of the major limitations of current thermal manikins are the restricted motions/postures (e.g., walking but not lifting) and segmentation into body zones that might be too large to realistically test highly localized devices (e.g., covering only part of the thigh). We did not measure the impact of walking on the thermal resistances of the exosuits because the changes imposed by such motion might be different from those imposed by lifting (for which the exosuit is designed). This issue can be resolved by the development of manikin motion stands relevant to the particular type of work tasks and wearable devices (e.g., lifting and walking stand). Regarding localized skin testing, a manikin with adjustable thermal zones could address the issue; otherwise, such measurements require additional external sensors. To increase the reliability and accuracy of the adaptive mode results, validation against more comprehensive human subject trials involving exosuits under relevant conditions should be conducted.

A limitation of the thermal comfort algorithm in thermal manikin's adaptive mode is its restricted capacity to measure skin wettedness, which is a primary contributor to thermal discomfort in hot weather conditions (Filingeri and Havenith, 2015; Fukazawa and Havenith, 2009; Raccuglia et al., 2018). This factor is starting to be implemented when assessing the suitability of a wearable device for thermal comfort in hot environments (e.g., headgear (Bogerd et al., 2015; Bröde et al., 2023)). While not directly addressing the skin wettedness, we measured a substantially lower back water vapor resistance for Exo2. Such feature should result in reduced sweat accumulation and lower skin wettedness, ultimately improving thermal comfort and the overall wearability of Exo2 in hot environments.

To analyze heat stress in the work environment and mitigation measures for a broader population, thermoregulation models need to consider gender, age, body mass index, anatomic details, acclimation, and the hydration level of individuals. The excessive sweating caused by intense activity and hot/humid exposure affects the material properties of fabric/exosuits (e.g., thermal conductivity in wet state). Furthermore, complex motion such as lifting significantly affect the underlying heat and mass transfer mechanisms (e.g., pumping effect and ventilation (Joshi et al., 2023)) which needs to be considered for the optimization of the exoskeletons. Lastly, the assumption of 30% reduction in metabolic heat (for lifting activities) due to assistive forces of the exosuits may not be applicable to all the cases, as workers perform other activities such as walking and standing along with the lifting.

4. Conclusions

Commercially available exoskeletons and exosuits can provide biomechanical support in various work tasks but can sometimes cause thermal discomfort for the user. We demonstrated that a sweating thermal manikin can be used to quantify the thermal properties (thermal and evaporative resistances) of exosuits, thereby providing a systematic platform for rapid evaluation of different device designs aiming at the improvement of the users' thermal comfort. Specifically, we analyzed the designs of legacy and recently released lower-back supporting exosuits over two different types of clothing ensembles (standard clothing and summer wear). The legacy exosuit covered nearly the entire back resulting in a significant increase in the corresponding thermal and evaporative resistances. The ~50% perforation of the area introduced in the updated exosuit mostly mitigated these undesired effects.

We also applied the adaptive mode thermal manikin (thermal manikin coupled with the human thermoregulation model) to evaluate human thermophysiological response to wearing an exosuit. In particular, we were able to replicate changes in local skin temperature (at the thigh), thermal comfort, and thermal sensation observed during a human trial involving release detachment of the thigh body interfaces. We also simulated prolonged heavy work in a hot and humid environment with recommended work/rest cycle with 5 to 30% reduction in metabolic heat that exosuits could provide. The results suggest that the reduction of the metabolic rate associated with wearing an exosuit could decrease the core temperature elevation and reduce sweat rates during intense activities, thereby decreasing thermal strain and dehydration. Consequently, our results suggest that exosuits could provide an additional approach to reduce occupational heat strain in increasingly frequent hot weather. Our study also demonstrates that thermal manikins coupled with thermoregulation models are an effective and efficient platform for comparing the thermal features of exosuits. Besides optimizing existing design features, thermal manikins could also be used to design devices that wholistically aim to improve the thermal safety and comfort of users working in hot conditions by integrating mechanical support with personal cooling garments (Martinez-Albert et al., 2023) to create “cool future fashion” (Rykaczewski, 2019).

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