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Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task

Authors

Shahnawaz Anwer, PhD Candidate,[1]; Email: shahnawaz.anwer@connect.polyu.hk
Professor Heng Li, PhD,[1]; Email: heng.li@polyu.edu.hk
Dr. Maxwell Fordjour Antwi-Afari, PhD,[2]: Email: m.antwiafari@aston.ac.uk
Dr. Waleed Umer, PhD,[3]; Email: Waleed.umer@kfupm.edu.sa
Imran Mehmood, PhD Candidate[1]; Email: imran.mehmood@connect.polyu.hk
Dr. Arnold Yu Lok Wong, PhD[4]; Email: arnold.wong@polyu.edu.hk

Affiliations

1. Department of Building and Real Estate, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region.
2. Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham, B4 7ET, United Kingdom,
3. Department of Construction Engineering & Management, King Fahd University of Petroleum & Minerals, Saudi Arabia
4. Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region.

*Corresponding author

Shahnawaz Anwer, MPT, PhD candidate
ZN1002, Smart Construction Laboratory
Department of Building and Real Estate
Faculty of Construction and Environment, The Hong Kong Polytechnic University
Kowloon, Hong Kong
Email: shahnawaz.anwer@connect.polyu.hk, anwerphysio@gmail.com

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Abstract

Purpose – Since construction workers often need to carry various types of loads in their daily routine, they are at risk of sustaining musculoskeletal injuries. Additionally, carrying a load during walking may disturb their walking balance and lead to fall injuries among construction workers. Different load carrying techniques may also cause different extents of physical exertion. Therefore, this study aimed to examine the effects of different load-carrying techniques on gait parameters, dynamic balance, and physiological parameters in asymptomatic individuals on both stable and unstable surfaces.

Design/methodology/approach – Fifteen asymptomatic male participants (mean age: 31.5 ± 2.6 years) walked along an 8-meter walkway on flat and foam surfaces with and without a load thrice using three different techniques (e.g., load carriage on the head, on the dominant shoulder, and in both hands). Temporal gait parameters (e.g., gait speed, cadence, and double support time), gait symmetry (e.g., step time, stance time, and swing time symmetry), and dynamic balance parameters [e.g., anteroposterior and mediolateral center of pressure (CoP) displacement, and CoP velocity] were evaluated. Additionally, the heart rate (HR) and electrodermal activity (EDA) was assessed to estimate physiological parameters.

Findings – The gait speed was significantly higher when the load was carried in both hands compared to other techniques (Hand load, 1.02 ms vs Head load, 0.82 ms vs Shoulder load, 0.78 ms). Stride frequency was significantly decreased during load carrying on the head than the load in both hands (46.5 vs 51.7 strides/m). Step, stance, and swing time symmetry were significantly poorer during load carrying on the shoulder than the load in both hands (Step time symmetry ration, 1.10 vs 1.04; Stance time symmetry ratio, 1.11 vs 1.05; Swing time symmetry ratio, 1.11 vs 1.04). The anteroposterior (Shoulder load, 17.47 mm vs Head load, 21.10 mm vs Hand load, -5.10 mm) and mediolateral CoP displacements (Shoulder load, -0.57 mm vs Head load, -1.53 mm vs Hand load, -3.37 ms) significantly increased during load carrying on the shoulder or head compared to a load in both hands. The HR (Head load, 85.2 beats/m vs Shoulder load, 77.5 beats/m vs No load, 69.5 beats/m) and EDA (Hand load, 14.0 µS vs Head load, 14.3 µS vs Shoulder load, 14.1 µS vs No load, 9.0 µS) were significantly larger during load carrying than no load.

Practical implications – Our findings suggest that carrying loads in both hands yields better gait symmetry and dynamic balance than carrying loads on the dominant shoulder or head. Construction managers/instructors should recommend construction workers to carry loads in both hands to improve their gait symmetry and dynamic balance and to lower their risk of falls.

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Originality/value – This is the first study to use wearable insole sensors and a photoplethysmography device to assess the impacts of various load carrying approaches on gait parameters, dynamic balance, and physiological measures (i.e., HR, and EDA) while walking on stable and unstable terrains.

Keywords: Gait; Balance; Fatigue; Construction safety; Wearable sensors

1. Introduction

Falls are the most common cause of workplace injuries, accounting for approximately 15-30% of occupational accidents (Kim and Robinson, 2005, Ling et al., 2009, Nenonen, 2013). Specifically, falls on the same level are the leading cause of workplace accidents, resulting in about 19% of nonfatal accidents among construction workers (Labour, 2017, Scott et al., 2018). The US Bureau of Labor Statistics revealed that approximately 36% of fatalities in the USA were related to fall accidents in construction workers (Dong et al., 2017, Statistics, 2016). The Hong Kong construction industry paid HKD 39 million as work compensation for nonfatal fall injuries in 2008 (Li and Poon, 2013). Therefore, it is utmost important to identify relevant risk factors for fall injuries in construction workers.

Both intrinsic (e.g., age, fatigue, work experience) and extrinsic (e.g., uneven surface, slippery floor, weight of load carriage, oversize carriage, etc.) factors may heighten the risk of fall incidence at construction sites (Bentley and Haslam, 2001, Gauchard et al., 2001). Many construction tasks can increase the risk of falls (Allin

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and Madigan, 2020, Parijat and Lockhart, 2008, Kazar and Comu, 2021). Umer et al. (2018c) has shown that prolonged squatting may cause lower limb fatigue, which induces immediate deterioration in static balance. Similarly, different load carrying methods can also affect the rate of physical fatigue and dynamic balance (Balogun, 1986, Hsiang and Chang, 2002, Iqbal and Thakurta, 2017, Simpson et al., 2011, Majumdar et al., 2010, Qu et al., 2020).

Since blue collar workers (e.g., construction workers) often need to carry various types of loads in their daily manual material handling (MMH) (Cheng et al., 2013, Alamoudi et al., 2018, Rodriguez et al., 2019), they are at risk of sustaining both traumatic and non-traumatic injuries during load carrying (Schaub, 2006, Umer et al., 2018a). Carrying a load during MMH is a known high risk procedure that accounts for approximately 33% of total low back pain cases in workplaces (Plamondon et al., 2010, Safety and Group, 1994). The incidence of musculoskeletal injuries is high in construction workers, particularly when performing tasks involving heavy load carrying (Hengel et al., 2012, Anwer et al., 2021b). Additionally, carrying a load during walking might disturb the walking balance and lead to more than 30% of fall injuries among Swedish construction workers (Andersson and Lagerlof, 1983).

Of the various carrying techniques, carrying loads on the head, shoulder, and in both hands are the most common techniques used by manual laborers (Bostrand and Frykman, 1992). Previous studies have reported that carrying loads on the head is more physically demanding than carrying loads on other body parts such as shoulders and hands (Soule and Goldman, 1969, Choi, 2012). Additionally, carrying loads on the head may cause undue pressure on the neck muscles leading to mechanical neck pain (Soule and Goldman, 1969). Carrying loads on the shoulder and hands may cause severe joint and muscle problems in addition to nerve injury (Mäkelä et al., 2006, Davis and Kotowski, 2007). Furthermore, different load carrying techniques may affect physical exertion and energy consumption (Stuempfle et al., 2004, Zultowski and Aruin, 2008). Previous researchers have recommended that proper load carrying techniques should put the carrying load in a more central body location rather than in unilaterally or asymmetrical locations(s) (such as on the shoulder or in one hand) (Zultowski and Aruin, 2008, Macias et al., 2008). Additionally, the load should be carried close to the center of mass of the body to minimize the balance disturbance created by the additional external loads (Knapik et al., 1997, Knapik et al., 1996).

Many studies have investigated the optimal methods for carrying a load during walking to minimize physical exertion (Legg et al., 1992, Abe et al., 2004, Pal et al., 2007, Chatterjee et al., 2012). However, these studies only assessed energy expenditure or oxygen consumption that may lead to exertion. Recently, heart rate (HR) and electrodermal activity (EDA) have been found as important indicators of physical and mental exertion (Epps, 2018, Collet et al., 2014, Anwer et al., 2020). Furthermore, carrying a load in one hand corresponds to a higher HR than carrying a load in two hands (Irion et al., 2010). However, there has been no study that has employed EDA to quantify physical exertion during various load-carrying activities.

To date, it remains unclear how different load carrying methods affect gait parameters, dynamic balance, and fatigue-related physiological changes (HR and EDA). Thus, the current study sought to determine the effects of various load carrying techniques on gait parameters, dynamic balance, HR, and EDA when walking on stable and unstable surfaces.

2. Literature review

While many studies have investigated static balance control during load transfer (Catena et al., 2010, Catena et al., 2011, Antwi-Afari et al., 2018), after prolonged static posture (Umer et al., 2018b, Umer et al., 2018c) and its relation with load magnitude (Zultowski and Aruin, 2008, Scholz et al., 1995, Lee, 2015), only a few studies have compared the effects of different load carrying techniques on gait parameters and dynamic balance (Hsiang and Chang, 2002, Iqbal and Thakurta, 2017). For example, Iqbal and Thakurta (2017) investigated the influences of three different load carrying techniques (i.e., head load, shoulder load, and hand load) on three gait parameters (e.g., stride length, stride width, and gait speed) in industrial workers. They concluded that carrying a load on the head showed smaller gait deviations as compared to shoulder and hand loading. However, they did not examine other gait parameters and dynamic balance during load carrying, which was crucial for understanding the mechanism of falls during such activities (Hsiang and Chang, 2002). Since carrying a load may alter the body's inertial features (e.g., center of gravity and overall weight), the neuromuscular system may need to change the gait pattern in order to carry the load (Hsiang and Chang, 2002), compensate for changes in the body's inertia, and maintain dynamic balance (Pai and Patton, 1997).

The gait pattern and postural balance during load carrying differs from that during natural walking (Mummolo et al., 2016). A few studies have investigated the effects of load carrying on various gait parameters including cadence, velocity, and ground reaction forces (LaFiandra et al., 2003, Qu and Yeo, 2011, Das et al., 2012, Alamoudi et al., 2018). Likewise, gait symmetry is another important and well-recognized parameter for revealing an individual's gait pattern (Patterson et al., 2010a). Gait symmetry indicates the degree of gait control as it indicates the parallel function of various spatiotemporal gait parameters between both legs (Patterson et al., 2010a, Patterson et al., 2010b). Gait symmetry can be expressed as a symmetry ratio of the right and left spatiotemporal gait parameters (i.e., step time, swing time, stance time, or step length). Since carrying an external load during walking may alter the body's center of mass (CoM)(Alamoudi et al., 2018) and disturb dynamic balance (Zultowski and Aruin, 2008, Palumbo et al., 2001), a person with poor dynamic stability may demonstrate more gait asymmetry (Holbein and Redfern, 1994, Zultowski and Aruin, 2008). Therefore, assessment of gait symmetry during load carrying may assess balance control and predict the risk of falls during such activities.

Many studies have been conducted to determine the best strategies for carrying a load during walking to reduce physical exertion. For instance, Pal et al. (2007) and Chatterjee et al. (2012) used gas analysis to quantify the energy cost during different load carrying techniques and found that the energy cost was higher in carrying a distributed load (e.g., a load is distributed in a haversack, and hands) than a compact load (e.g., backpack or rucksack). Recently, Chatterjee et al. (2018) examined the effects of load carrying on cardiorespiratory and metabolic measures of exertion in military personnel. They found that carrying a distributed load induced significantly higher HR responses than a compact load. In addition to HR, EDA is an important measure to assess exertion during physical and mental workload (Epps, 2018, Collet et al., 2014, Anwer et al., 2020). While many ergonomic studies have used EDA to objectively quantify mental fatigue (Gevins and Smith, 2003, Reimer and Mehler, 2011, Just et al., 2003), no study has used EDA to measure physical exertion during different load-carrying tasks, which may provide new insight into physiological changes. Recently, Giagloglou et al. (2019) assessed physical and mental loads related to MMH tasks with different load configurations. They reported significant increases in EDA values for a fully loaded pushing cart compared to no load pushing cart.

Recent advancements and feasibility of wearable sensors (e.g., photoplethysmography, insole sensors, etc.) in the construction industry have made possible a real-time monitoring of biomechanical and physiological data to measure gait parameters, dynamic balance, and physical exertion without interfering worker’s daily activities (Edirisinghe, 2019, Antwi-Afari et al., 2020b, Antwi-Afari et al., 2019, Kazar and Comu, 2021, Anwer et al., 2021a). For example, Antwi-Afari et al. (2020b) indicated an excellent test-retest reliability (Intraclass correlation coefficient = 0.91) and good validity (Intraclass correlation coefficient = 0.75) of a wearable insole pressure system to measure gait parameters in a laboratory setting. A recent study has suggested that monitoring of physiological data including HR using the photoplethysmography based wristband can reliably indicate physical exertion in construction workers (Kazar and Comu, 2021). Therefore, the current study used a photoplethysmography based wristwatch and a wearable insole pressure system for the real-time monitoring of the gait parameters, dynamic balance, HR, and EDA while a worker performed a walking task with different load carrying techniques on stable and unstable surfaces.

3. Methods

3.1. Participants

Fifteen healthy students aged 18 years or older (Mean age, 31.5 ± 2.6 years) were recruited by convenient sampling. Table 1 represents the demographic details of all participants. Individuals with a history of musculoskeletal or neurological disorders were excluded. The study was approved by the ethics subcommittee of the university (Reference Number: HSEARS20191008004) and conducted in accordance with the Declaration of Helsinki. Participants provided informed consent.

<Please insert Table 1 about here>

3.2. Instrumentation

3.2.1. Assessment of gait and dynamic balance

Novel commercially available wearable insoles with plantar pressure sensors (OpenGo system, Moticon SCIENCE Sensor, Insole, GmbH, Munich, Germany) as shown in **Figure 1** were used to quantify the gait and dynamic parameters (Refai et al., 2018, Stöggl and Martiner, 2017, Antwi-Afari et al., 2018, Antwi-Afari et al., 2020b). The smart insoles with different sizes can fit in any shoe. The recorded gait data collected by the smart insoles was transferred wirelessly via an ANT radio service (Stöggl and Martiner, 2017). Each pair of insoles comprised 16 pressure sensors and a 6-axis gyroscope to assess the angular velocity and acceleration of average foot pressure at different areas. The hysteresis, range, and resolution of pressure sensors are < 1%, 0 to 50.0 N/cm^2, and 0.25 N/cm^2, respectively. The angular rate and acceleration range are ± 2000 degrees/second and ± 16g, respectively. The frequency of sampling data is 50 Hz (Antwi-Afari et al., 2020a). Temporal gait parameters (e.g., gait speed, cadence, double support time, step duration, stance duration, and swing duration) and dynamic stability [the anteroposterior and mediolateral center of pressure (CoP) displacements, and mean sway velocity in the anteroposterior and mediolateral directions] were collected (Oerbekke et al., 2017, Phan-Ba et al., 2012). Participants were asked to walk at the usual speed along an 8-meter walkway as a trial before the actual data collection. The walking speed was calculated by dividing the 8 meters by the time required to complete the walkway (Oerbekke et al., 2017).

<Please insert Figure 1 about here>

3.2.2. Assessment of physiological parameters

To measure HR and EDA, a photoplethysmography (PPG) wristwatch (Empatica E4) as shown in **Figure 2** was used. The PPG wristwatch comprises 4 light emitting diodes and 4 photoreceptors. The HR data was estimated based on the variations in the intensity of the refracted light due to fluctuations in blood flow (Tamura et al., 2014, Pietilä et al., 2017). HR data is calculated for every second via an Empatica E4 algorithm (Milstein and Gordon, 2020). The HR datasheet includes one column, which indicates HR data sampled at 64 Hz (Milstein and Gordon, 2020). Empatica E4 uses two sensors to automatically monitor fluctuating changes in the actual electrical properties of the skin, which is used to derive EDA (Milstein and Gordon, 2020). The EDA datasheet contains one column, which indicates EDA data in MicroSiemens sampled at 4 Hz (Milstein and Gordon, 2020). A special software such as Ledalab, which is freely available, is used in the current study to derive cleaned, scaled, and meaningful EDA data. Movement artifacts were manually identified and edited. The EDA was estimated in MicroSiemens for every 500 ms with a rolling filter of 500 data points (Posada-Quintero and Chon, 2020).

<Please insert Figure 2 about here>

3.3. Experimental procedures

The experimental methods are illustrated in **Figure 3**. All participants filled out a self-reported questionnaire to provide their demographics information and medical history. Participants were then instructed to wear a pair of wearable insoles to assess potential changes in gait parameters and dynamic balance. They also put on a PPG wristwatch to evaluate the physical exertion related physiological parameters (HR and EDA) during different load-carrying tasks. All participants did a practice trial of each experimental task before the actual data collection. Specifically, they were instructed to walk down an 8-meter flat (stable) or foam (unstable) surface (8 m * 0.9 m* 0.01 m) walkway for a stable or unstable trial, respectively. Foam surface was used for unstable trial because it is not uncommon that construction sites have various uneven and unstable terrains, which can heighten the risk of slips, trips, and falls (Antwi-Afari and Li, 2018). Upon completion of three unloaded walking trials, participants were asked to carry a 15kg ergonomically designed wooden box load using each of the three load carrying methods (load carriage on the head, on the dominant shoulder, and in both hands) thrice on stable and unstable surfaces with a 2-minute break between successive trials. This selected load weight was a typical weight of materials being carried out during MMH tasks at workplaces (Zhang, 2014). The order of the load carrying techniques was randomized to avoid any order effect (Carraça et al., 2018). Participants were asked to perform the load carrying method by walking on an unstable surface (e.g., the foam surface) to challenge their dynamic balance. Previous studies have used foam surfaces to measure CoP parameters for assessing dynamic balance (Teasdale et al., 1991, Creath et al., 2005). A foam surface can modify the ground reaction forces and increase the frequency and amplitude of body sway (Desai et al., 2010, Antwi-Afari et al., 2017). Therefore, participants had to respond to the sway by increasing balance control and automatic postural adjustment to prevent falls (Desai et al., 2010). Participants were instructed to use their normal walking speed for both stable and unstable trails.

<Please insert Figure 3 about here>

3.4. Statistical analysis

Data was analyzed using SPSS version 22 (IBM Inc., Chicago, IL). Descriptive and inferential statistics were used. The Shapiro–Wilk test was used to check the normality of data. The temporal gait parameters (e.g., gait speed, cadence, double support time, step duration, stance duration, and swing duration), gait symmetry ratio (step, stance, and swing time symmetry), dynamic balance (CoP displacement and velocity), and physiological data (e.g., HR and EDA) were considered as dependent variables. Gait symmetry ratios were calculated based on the average value of step, stance, or swing time of the left and right legs. The larger value was considered as a numerator so that all symmetry ratios were ≥ 1 for each individual. A ratio value of 1 indicates a perfect symmetry (Patterson et al., 2010b). Repeated measures analyses of variance (ANOVAs) with Bonferroni correction for post hoc tests were used to compare the effects of different load carrying conditions (no load, hand load, shoulder load, and head load) on gait, dynamic balance, HR, and EDA. Mauchly's test was used to determine sphericity. Greenhouse-Geisser estimation was used for non-sphericity data. The effect size of each data was analyzed using partial eta-squared (η^2) statistics. The alpha value was set at 0.05.

4. Results

4.1. Gait parameters during different load carrying conditions

Table 2 presents the changes in gait parameters during different load carrying conditions. There was a significant difference in gait speed across the three load carrying techniques. Compared with the average gait speed without load, the average decreases in gait speed with load carried in the hands, on the head, and the dominant shoulder were 0.18 m/s, 0.38 m/s, and 0.42 m/s, respectively. The cadences (strides/minute) during the load carrying on the head were significantly lower than those during load carrying in both hands. However, all three techniques had no significant difference in cadence compared to no load. Comparing with walking without load, the double support times during load carrying in both hands, on the head and shoulder were significantly longer by 0.15s, 0.25s, and 0.23s, respectively. More gait asymmetries in step, stance, and swing time were noted during load carrying on the dominant shoulder compared to load carrying in both hands or without load.

<Please insert Table 2 about here>

4.2. Dynamic balance parameters during different load carrying conditions

Table 3 and **Figure 4** present the changes in balance parameters during different load carrying techniques compared to no load. The anteroposterior and mediolateral CoP displacements were significantly increased during load carrying on the dominant shoulder or head compared to load in both hands or no load. The mean COP velocity was significantly smaller during all three load carrying techniques compared to no load (p=0.004). The anteroposterior CoP displacement during load carrying in both hands was significantly greater than no load (mean difference = 16.13 mm), load on the head (mean difference = 26.20 mm) or load on the dominant shoulder (mean difference = 22.57 mm). The mediolateral CoP displacement was significantly increased during load carrying on the head (mean difference = 1.83 mm) and shoulder (mean difference = 2.80 mm) compared to load carrying in both hands.

While there was no significant difference in CoP velocity of the left foot across different load carrying conditions, significant differences in CoP velocity of the right foot were noted during different load carrying conditions. In particular, the CoP velocity of the right foot during load carrying in both hands (mean difference = 105.678 mm/s), on the head (mean difference = 82.43 mm/s), or on the dominant shoulder (mean difference = 84.03 mm/s) was significantly lower than that during walking without load.

We also compared the balance parameters between stable (floor) and unstable (foam) surfaces. Table 4 presents comparison of balance parameters between stable and unstable surfaces. There were no significant differences in all parameters between stable and unstable surfaces except the CoP velocity.

<Please insert Table 3 about here>

<Please insert Figure 4 about here>

<Please insert Table 4 about here>

4.3. Physiological parameters *(HR and EDA) during different load carrying*

conditions

Table 5 shows the changes in physiological parameters during different load carrying techniques compared to no load. **Figure 5** depicts comparison of physiological changes during the load carriage tasks. The HR during load carrying on the dominant shoulder (mean difference = 8.0 beats/min) or the head (mean difference = 15.7 beats/min) was significantly higher than that under no load condition. Likewise, load carrying in both hands (mean difference = 5.00 μS/cm), on the shoulder (mean difference = 5.15 μS/cm) or the head (mean difference = 5.38 μS/cm) yielded significantly higher EDA values than the no load condition.

<Please insert Table 5 and Figure 5 about here>

5. Discussion

The current study revealed significant changes in gait symmetry, dynamic balance, HR, and EDA associated with different load-carrying techniques (e.g., load carrying in both hands, on the shoulder or head) compared to walking without load along an 8-m walkway.

5.1. Changes in the gait parameters

Carrying a load in both hands showed better gait parameters. Gait speed was the lowest when carrying the load on the dominant shoulder and the highest with the load in both hands. Cadence (stride/min) was the lowest while carrying the load on the head and the highest while carrying the load in both hands. Furthermore, the double support time was the highest with the load on the head and the lowest with the load in both hands. Similarly, a better symmetry in step time, stance time, or swing time was noted when carrying the load in both hands compared to load carrying on the head or shoulder. Guha Thakurta et al. (2017) also reported significant differences in various gait parameters including stride length, gait cycle time, cadence, and gait velocity during different load carrying techniques. Unlike the current findings, they reported walking on a 75-meter walkway with a carrying load of 30 kg on the head, having the highest gait speed followed by shoulder and hands (Guha Thakurta et al., 2017). They also showed longer step duration and double support time when carrying the load in hands and the lowest with the load on the head (Guha Thakurta et al., 2017). The swing duration was the shortest with the load in the hands and the longest with the load on the head (Guha Thakurta et al., 2017). Similar to our study, they found that carrying a load in both hands yielded the highest cadence, followed by the shoulder and head (Guha Thakurta et al., 2017). However, a direct comparison between the two studies is inappropriate due to different participants, loads, and distance. Additionally, the current study recruited healthy construction students as participants, while the previous study recruited healthy construction workers. Experienced construction workers might be more capable in performing dual tasks (i.e., carrying a load and walking with normal gait patterns) than university students. That said, our findings might represent the performance of young construction workers (ages between 18 to 24 years old), who are known to have a higher workplace injury rate than older counterparts according to the European Risk Observatory Report 2006 construction workers compared to older workers (Verjans et al., 2007). Other studies also reported that young to middle aged construction workers had a high risk of workplace injuries (Hong Tu and LM, 2008, Mehrdad et al., 2014, Khodabandeh et al., 2016).

5.2. Changes in dynamic balance parameters

Participants walking with a carrying load on the head or on the dominant shoulder demonstrated poor dynamic balance compared to those who carried the load in both hands. Increased deviation in anteroposterior and mediolateral CoP displacements during load carrying may indicate reduced dynamic balance control. An additional load, carrying a load higher off the ground, and postural asymmetry may disturb the dynamic balance/stability (Holbein and Redfern, 1994). Previous research reported that carrying loads may increase postural sway as shown by increased anteroposterior and mediolateral CoP displacements (Zultowski and Aruin, 2008). In particular, carrying a load at a greater distance away from the ground may result in poorer balance (Holbein and Redfern, 1994). Furthermore, carrying loads asymmetrically can elicit significantly greater mediolateral CoP deviation than no load carrying (Holbein and Redfern, 1994). Previous research found that an asymmetrical load carrying affected CoP displacement, especially in the mediolateral direction (Zultowski and Aruin, 2008). Since an increased deviation in mediolateral CoP displacement is predictors for falls (Caderby et al., 2017), asymmetrical load carrying techniques (e.g., load carrying with a shoulder) may increase the risk of falls and increase the asymmetrical loading of the spine (Zultowski and Aruin, 2008).

5.3. Changes in physiological parameters

The HR and EDA were the highest when participants carried a load on the head, followed by the shoulder and hands. These values in all three load carrying techniques were significantly higher than those under the no load condition. These findings concurred with prior findings that carrying load inducted greater HR than walking alone (Tseng and Liu, 2011). However, our findings differed from another study that showed the highest HR when carrying a load in both hands followed by on the shoulder or head (Guha Thakurta et al., 2017). However, a direct comparison between the two studies is inappropriate due to different participants and loads. Additionally, the current study recruited healthy construction students as participants, while the previous study recruited healthy construction workers. Experienced construction workers might be more capable of carrying loads on the head or shoulder without much physical effort than university students.

Since no past studies examined changes in EDA during loading and unloading conditions, a direct comparison of the current findings with past research are impossible. While a few studies reported increased EDA under physical load (Sato and Dobson, 1970, Sawka et al., 2010), other studies have found increased EDA under mental workload (Marcora et al., 2009, Tian et al., 2011). Therefore, future studies are warranted to examine changes in EDA under different load carrying techniques.

5.4. Comparison of load carrying approaches according to the published literature

Table 6 summarizes the comparisons made between various studies on the influence of different load carrying approaches. Carrying loads is a common activity in the construction industry. Despite automation in the construction industry, the demand for manually transferring relatively heavy goods remains to be an important occupational activity for construction workers. Manually carrying a load can be done in various ways. The technique of load carriage chosen is determined by several factors, including the quantity and volume of the weight, the distance to be carried, the terrain, and the physical quality of an individual. Load carrying is a strenuous activity that requires muscle contraction and may cause both visible and invisible injuries of the musculoskeletal system. Carrying a load in hands or on a shoulder or head can have different ergonomic implications. If construction workers have a history of lower back discomfort or would like to reduce future episodes of low back pain, carrying a load in both hands induced significantly less spinal compressive load and muscle activation force than carrying a load in one hand (McGill et al., 2013). A previous study showed that carrying load in two-hands outperformed one-hand carrying in terms of lower cardiac cost, less maximum voluntary contraction (%), and lower perceived discomfort (Ramadan et al., 2018). Das et al. (2012) revealed that carrying a load in both hands produced better gait characteristics than carrying a load in one hand. Additionally, Alamoudi et al. (2018) found that carrying a load in one hand and forward loading induced the most unstable gait when compared to carrying a load in both hands and posterior loading.

<Please insert Table 6 about here>

6. Limitations and future research directions

The current study had several limitations. First, the distance and amount of load carried were relatively small. The findings may not be generalized to heavier loads or a longer carrying distance. Future studies are warranted to investigate changes in gait patterns, balance, and physiological parameters associated with different load carrying weights and/or longer durations of MMH activity. Second, load carrying techniques were performed using an ergonomically designed square shape wooden box. However, workers at construction sites may need to carry irregular shaped objects without ergonomic designs. Carrying a large irregular shaped object may could force a worker to adopt an awkward posture, which can disturb balance/stability (Birrell and Haslam, 2010). Future studies should assess gait, dynamic balance, and physiological parameters while carrying irregular objects using different load carrying techniques. Third, the current study only assessed the effects of different load carrying techniques on kinematic and physiological parameters during level ground walking. Working on other surfaces such as slippery or inclined surfaces may compromise gait and balance control (Bunterngchit et al., 2000, Grönqvist, 1999), as well as increase the risk of slips and falls (Cham and Redfern, 2004, Courtney et al., 2001, Antwi-Afari et al., 2020b). Therefore, it is necessary to investigate the effects of different terrains on gait stability. Fourth, the participants in this study were young, and mainly students. Therefore, future research should investigate the impacts of different load carrying techniques in middle-aged and old construction workers, who are known to have poorer gait and balance controls (Iosa et al., 2014).

7. Study implications and practical contributions

This is the first study to use wearable insole sensors and a PPG device to assess the impacts of various load carrying approaches on gait parameters, dynamic balance, and physiological measures (i.e., HR, and EDA) while walking on stable and unstable terrains. Our results have both theoretical and pragmatic implications for construction workers. First, it is feasible to use a wearable insole pressure system to monitor the changes in gait (e.g., gait speed, cadence, and gait symmetry) and balance parameters (e.g., anteroposterior and mediolateral CoP displacements) associated with different load carrying approaches. The identified gait and balance abnormalities during various load carrying approaches will help analyze fall related risk in construction workers during loaded walking. Specifically, the real-time monitoring of gait and balance by wearable insole sensors would allow safety managers to identify workers with a higher risk of falls during load carriage owing to various factors (e.g., physical exertion, fatigue, improper load carrying techniques). It will also empower these managers to take necessary steps to prevent falls. Consequently, our results lay the foundation for construction stakeholders (especially construction managers) to educate their workers regarding a safer load carrying technique to maintain a better gait pattern and dynamic balance, which may lower the risk of fall injuries. Second, this study used a noninvasive method for the real-time assessment of physiological measures such as HR and EDA during different load carrying approaches. Construction site managers may utilize this method to monitor construction workers who are at risk of physical fatigue during the load carriage tasks. Additionally, our findings could help develop or update MMH guidelines for load carrying based on wearable insole sensors and a PPG device data. In particular, the use of PPG devices for real-time physical risk assessments during construction tasks can be recommended as a new approach to improve the monitoring and education of workplace safety in construction workers. Further, future research should focus on developing a personalized wearable warning system that uses machine learning approach to automatically capture and analyze gait, dynamic balance, and physiological parameters to identify real-time safety hazards related to load carriage tasks. Moreover, while this study substantiated changes in gait and balance stability in different carrying techniques, we recommend more in-depth analysis of kinetic and kinematic data using machine learning approach in future studies, which would improve our understanding about different load carrying techniques during various construction tasks.

8. Conclusions

This study evaluated the effects of different load-carrying techniques on gait parameters, dynamic balance, and physiological parameters in asymptomatic individuals on both stable and unstable surfaces using photoplethysmography sensors and a wearable insole pressure system. The gait speed was 25% – 30% higher when carrying a load in both hands as compared to load carrying on the dominant shoulder or head. However, the stride frequency was significantly lower (11%) when carrying a load on the head than when carrying a load in both hands. The anteroposterior and mediolateral CoP displacements increased significantly while carrying a load on the shoulder (3.4 and 0.5 times, respectively) or head (4.1 and 0.2 times, respectively) as compared to a load in both hands. All three load carrying techniques induced significant increases in HR and EDA from baseline. Our findings provide empirical data to support that carrying a load in both hands yields better gait symmetry and dynamic balance than load carrying on the dominant shoulder or head. However, the three different load carrying techniques still induce similar levels of physiological response. The potential changes in gait and balance parameters during various load carrying methods will aid the assessment of fall risk in construction workers during loaded walking. Wearable insole sensors that monitor gait and balance in real-time would enable safety managers to identify workers who are at risk of falling during load carriage due to various reasons (e.g., physical exertion, improper carrying techniques, fatigue). Such technology can also empower them to take the necessary steps to prevent falls. Future field studies should assess the effects of different load carrying techniques or shapes of carrying objects on the gait, balance, and physiological parameters of construction workers on different working surfaces.

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

Reference

ABE, D., YANAGAWA, K. & NIIHATA, S. 2004. Effects of load carriage, load position, and walking speed on energy cost of walking. *Applied ergonomics,* 35**,** 329-335.

ALAMOUDI, M., TRAVASCIO, F., ONAR-THOMAS, A., ELTOUKHY, M. & ASFOUR, S. 2018. The effects of different carrying methods on locomotion stability, gait spatio-temporal parameters and spinal stresses. *International Journal of Industrial Ergonomics,* 67**,** 81-88.

ALLIN, L. J. & MADIGAN, M. L. 2020. Effects of Manual Material Handling Workload on Measures of Fall Risk. *IISE transactions on occupational ergonomics and human factors***,** 1-11.

ANDERSSON, R. & LAGERLOF, E. 1983. Accident data in the new Swedish information system on occupational injuries. *Ergonomics,* 26**,** 33-42.

ANTWI-AFARI, M. F. & LI, H. 2018. Fall risk assessment of construction workers based on biomechanical gait stability parameters using wearable insole pressure system. *Advanced Engineering Informatics,* 38**,** 683-694.

ANTWI-AFARI, M. F., LI, H., ANWER, S., YEVU, S. K., WU, Z., ANTWI-AFARI, P. & KIM, I. 2020a. Quantifying workers’ gait patterns to identify safety hazards in construction using a wearable insole pressure system. *Safety Science,* 129**,** 104855.

ANTWI-AFARI, M. F., LI, H., EDWARDS, D. J., PÄRN, E. A., SEO, J. & WONG, A. 2017. Effects of different weights and lifting postures on balance control following repetitive lifting tasks in construction workers. *International Journal of Building Pathology and Adaptation*.

ANTWI-AFARI, M. F., LI, H., SEO, J., ANWER, S., YEVU, S. K. & WU, Z. 2020b. Validity and reliability of a wearable insole pressure system for measuring gait parameters to identify safety hazards in construction. *Engineering, Construction and Architectural Management*.

ANTWI-AFARI, M. F., LI, H., SEO, J. & WONG, A. Y. L. 2018. Automated detection and classification of construction workers' loss of balance events using wearable insole pressure sensors. *Automation in Construction,* 96**,** 189-199.

ANTWI-AFARI, M. F., LI, H., WONG, J. K.-W., OLADINRIN, O. T., GE, J. X., SEO, J. & WONG, A. Y. L. 2019. Sensing and warning-based technology applications to improve occupational health and safety in the construction industry. *Engineering, Construction and Architectural Management,* 26**,** 1534-1552.

ANWER, S., LI, H., ANTWI-AFARI, M. F., UMER, W. & WONG, A. Y. 2020.

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

Cardiorespiratory and Thermoregulatory Parameters Are Good Surrogates for Measuring Physical Fatigue during a Simulated Construction Task. *International Journal of Environmental Research and Public Health,* 17**,** 5418.

ANWER, S., LI, H., ANTWI-AFARI, M. F., UMER, W. & WONG, A. Y. 2021a. Evaluation of physiological metrics as a real-time measurement of physical fatigue in construction workers: State-of-the-Art Reviews. *Journal of Construction Engineering and Management*.

ANWER, S., LI, H., ANTWI-AFARI, M. F. & WONG, A. Y. L. 2021b. Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: A systematic review. *International Journal of Industrial Ergonomics,* 83**,** 103113.

BALOGUN, J. A. 1986. Ergonomic comparison of three modes of load carriage. *International archives of occupational and environmental health,* 58**,** 35-46.

BENTLEY, T. A. & HASLAM, R. 2001. Identification of risk factors and countermeasures for slip, trip and fall accidents during the delivery of mail. *Applied ergonomics,* 32**,** 127-134.

BIRRELL, S. A. & HASLAM, R. A. 2010. The effect of load distribution within military load carriage systems on the kinetics of human gait. *Applied ergonomics,* 41**,** 585-590.

BOSTRAND, L. & FRYKMAN, B. 1992. *Introduction to ergonomics in forestry in developing countries*, Food & Agriculture Org.

BUNTERNGCHIT, Y., LOCKHART, T., WOLDSTAD, J. C. & SMITH, J. L. 2000. Age related effects of transitional floor surfaces and obstruction of view on gait characteristics related to slips and falls. *International Journal of Industrial Ergonomics,* 25**,** 223-232.

CADERBY, T., YIOU, E., PEYROT, N., DE VIVIÉS, X., BONAZZI, B. & DALLEAU, G. 2017. Effects of changing body weight distribution on mediolateral stability control during gait initiation. *Frontiers in human neuroscience,* 11**,** 127.

CARRAÇA, B., SERPA, S., GUERRERO, J. P. & ROSADO, A. 2018. Enhance sport performance of elite athletes: the mindfulness-based interventions. *Cuadernos de Psicología del Deporte,* 18**,** 79-109.

CATENA, R. D., DIDOMENICO, A., BANKS, J. J. & DENNERLEIN, J. T. 2010. The effect of load weight on balance control during lateral box transfers. *Ergonomics,* 53**,** 1359-1367.

CATENA, R. D., DIDOMENICO, A., BANKS, J. J. & DENNERLEIN, J. T. 2011. Balance control during lateral load transfers over a slippery surface. *Ergonomics,* 54**,** 1060-1071.

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

CHAM, R. & REDFERN, M. S. 2004. Gait adaptations during load carrying on level and inclined surfaces. *Occupational Ergonomics,* 4**,** 11-26.

CHATTERJEE, S., CHATTERJEE, T., BHATTACHARYYA, D., SEN, S. & PAL, M. 2018. Effect of heavy load carriage on cardiorespiratory responses with varying gradients and modes of carriage. *Military Medical Research,* 5**,** 26.

CHATTERJEE, T., BHATTACHARYYA, D., PAL, M. & MAJUMDAR, D. 2012. Cardiorespiratory changes with compact backpack system and distributed mode of load carriage. *Indian J Physiol Pharmacol,* 56**,** 130-6.

CHENG, T., MIGLIACCIO, G. C., TEIZER, J. & GATTI, U. C. 2013. Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. *Journal of Computing in Civil engineering,* 27**,** 320-335.

CHOI, S. D. 2012. A study of trade-specific occupational ergonomics considerations in the US construction industry. *Work,* 42**,** 215-222.

COLLET, C., SALVIA, E. & PETIT-BOULANGER, C. 2014. Measuring workload with electrodermal activity during common braking actions. *Ergonomics,* 57**,** 886-896.

COURTNEY, T. K., SOROCK, G. S., MANNING, D. P., COLLINS, J. W. & HOLBEIN-JENNY, M. A. 2001. Occupational slip, trip, and fall-related injuries can the contribution of slipperiness be isolated? *Ergonomics,* 44**,** 1118-1137.

CREATH, R., KIEMEL, T., HORAK, F., PETERKA, R. & JEKA, J. 2005. A unified view of quiet and perturbed stance: simultaneous co-existing excitable modes. *Neuroscience letters,* 377**,** 75-80.

DAS, R., DHUME, R. & IYER, S. 2012. Effects of carrying symmetric and asymmetric weights on gait parameters and lateral spinal flexion. *International Journal of Engineering Science & Technology,* 4**,** 4571.

DAVIS, K. G. & KOTOWSKI, S. E. 2007. Understanding the ergonomic risk for musculoskeletal disorders in the United States agricultural sector. *American journal of industrial medicine,* 50**,** 501-511.

DESAI, A., GOODMAN, V., KAPADIA, N., SHAY, B. L. & SZTURM, T. 2010. Relationship between dynamic balance measures and functional performance in community-dwelling elderly people. *Physical therapy,* 90**,** 748-760.

DONG, X. S., LARGAY, J. A., CHOI, S. D., WANG, X., CAIN, C. T. & ROMANO, N. 2017. Fatal falls and PFAS use in the construction industry: Findings from the NIOSH FACE reports. *Accident Analysis & Prevention,* 102**,** 136-143.

EDIRISINGHE, R. 2019. Digital skin of the construction site: smart sensor technologies towards the future smart construction site. *Engineering, Construction and*

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

Architectural Management, 26**,** 184-223.

EPPS, J. 2018. Task load and stress. *The Wiley Handbook of Human Computer Interaction,* 1**,** 207-223.

GAUCHARD, G., CHAU, N., MUR, J. M. & PERRIN, P. 2001. Falls and working individuals: role of extrinsic and intrinsic factors. *Ergonomics,* 44**,** 1330-1339.

GEVINS, A. & SMITH, M. E. 2003. Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomics Science,* 4**,** 113-131.

GIAGLOGLOU, E., RADENKOVIC, M., BRANKOVIC, S., ANTONIOU, P. & ZIVANOVIC-MACUZIC, I. 2019. Pushing, pulling and manoeuvring an industrial cart: a psychophysiological study. *International Journal of Occupational Safety and Ergonomics,* 25**,** 296-304.

GRÖNQVIST, R. 1999. Slips and falls. *Biomechanics in ergonomics***,** 351-375.

GUHA THAKURTA, A., IQBAL, R. & DE, A. 2017. The influence of three different load carrying methods on gait parameters of Indian construction workers. *MOJ Anat Physiol,* 3**,** 00098.

HENGEL, K. M. O., BLATTER, B. M., GEUSKENS, G. A., KOPPES, L. L. & BONGERS, P. M. 2012. Factors associated with the ability and willingness to continue working until the age of 65 in construction workers. *International archives of occupational and environmental health,* 85**,** 783-790.

HOLBEIN, M. & REDFERN, M. Postural stability while walking and carrying loads in various postures. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1994. SAGE Publications Sage CA: Los Angeles, CA, 564-567.

HONG TU, N. & LM, A. 2008. Occupational injuries and prevention activities in Vietnam. *Asian-Pacific Newslett Ocup Health Saf,* 15**,** 7-10.

HSIANG, S. M. & CHANG, C. 2002. The effect of gait speed and load carrying on the reliability of ground reaction forces. *Safety Science,* 40**,** 639-657.

IOSA, M., FUSCO, A., MORONE, G. & PAOLUCCI, S. 2014. Development and decline of upright gait stability. *Frontiers in aging neuroscience,* 6**,** 14.

IQBAL, R. & THAKURTA, A. G. 2017. G1-2 Influence of different modes of load carriage on lower limb biomechanics of industrial workers. *The Japanese Journal of Ergonomics,* 53**,** S366-S370.

IRION, G., MELANCON, H. H., NUCHERENO, N., STRAWBRIDGE, B. & YOUNG, J. 2010. Cardiovascular responses to carrying groceries in bags with and without handles. *Journal of Acute Care Physical Therapy,* 1**,** 64-68.

JUST, M. A., CARPENTER, P. A. & MIYAKE, A. 2003. Neuroindices of cognitive workload: Neuroimaging, pupillometric and event-related potential studies of brain work. *Theoretical Issues in Ergonomics Science,* 4**,** 56-88.

KAZAR, G. & COMU, S. 2021. Exploring the relations between the physiological factors and the likelihood of accidents on construction sites. *Engineering, Construction and Architectural Management*.

KHODABANDEH, F., KABIR-MOKAMELKHAH, E. & KAHANI, M. 2016. Factors associated with the severity of fatal accidents in construction workers. *Medical journal of the Islamic Republic of Iran,* 30**,** 469.

KIM, B. J. & ROBINSON, C. J. 2005. Postural control and detection of slip/fall initiation in the elderly population. *Ergonomics,* 48**,** 1065-1085.

KNAPIK, J., HARMAN, E. & REYNOLDS, K. 1996. Load carriage using packs: a review of physiological, biomechanical and medical aspects. *Applied ergonomics,* 27**,** 207-216.

KNAPIK, J. J., ANG, P., MEISELMAN, H., JOHNSON, W., KIRK, J., BENSEL, C. & HANLON, W. 1997. Soldier performance and strenuous road marching: influence of load mass and load distribution. *Military medicine,* 162**,** 62-67.

LABOUR, A. 2017. 2016 Workplace Injury, Illness and Fatality Statistics Provincial Summary. Author Edmonton.

LAFIANDRA, M., WAGENAAR, R. C., HOLT, K. & OBUSEK, J. 2003. How do load carriage and walking speed influence trunk coordination and stride parameters? *Journal of biomechanics,* 36**,** 87-95.

LEE, T.-H. 2015. The effects of load magnitude and lifting speed on the kinematic data of load and human posture. *International Journal of Occupational Safety and Ergonomics,* 21**,** 55-61.

LEGG, S., RAMSEY, T. & KNOWLES, D. 1992. The metabolic cost of backpack and shoulder load carriage. *Ergonomics,* 35**,** 1063-1068.

LI, R. Y. M. & POON, S. W. 2013. Workers’ Compensation for Non-fatal Construction Accidents: Review of Court Cases in Hong Kong. *Construction Safety.* Springer.

LING, F. Y. Y., LIU, M. & WOO, Y. C. 2009. Construction fatalities in Singapore. *International Journal of Project Management,* 27**,** 717-726.

MACIAS, B. R., MURTHY, G., CHAMBERS, H. & HARGENS, A. R. 2008. Asymmetric loads and pain associated with backpack carrying by children. *Journal of Pediatric Orthopaedics,* 28**,** 512-517.

MAJUMDAR, D., PAL, M. S. & MAJUMDAR, D. 2010. Effects of military load carriage on kinematics of gait. *Ergonomics,* 53**,** 782-791.

MÄKELÄ, J. P., RAMSTAD, R., MATTILA, V. & PIHLAJAMÄKI, H. 2006. Brachial plexus lesions after backpack carriage in young adults. *Clinical Orthopaedics and*

Related Research®, 452**,** 205-209.

MARCORA, S. M., STAIANO, W. & MANNING, V. 2009. Mental fatigue impairs physical performance in humans. *Journal of applied physiology,* 106**,** 857-864.

MCGILL, S. M., MARSHALL, L. & ANDERSEN, J. 2013. Low back loads while walking and carrying: comparing the load carried in one hand or in both hands. *Ergonomics,* 56**,** 293-302.

MEHRDAD, R., SEIFMANESH, S., CHAVOSHI, F., AMINIAN, O. & IZADI, N. 2014. Epidemiology of occupational accidents in Iran based on social security organization database. *Iranian Red Crescent Medical Journal,* 16.

MILSTEIN, N. & GORDON, I. 2020. Validating Measures of Electrodermal Activity and Heart Rate Variability Derived From the Empatica E4 Utilized in Research Settings That Involve Interactive Dyadic States. *Frontiers in Behavioral Neuroscience,* 14.

MUMMOLO, C., PARK, S., MANGIALARDI, L. & KIM, J. H. 2016. Computational evaluation of load carriage effects on gait balance stability. *Computer methods in biomechanics and biomedical engineering,* 19**,** 1127-1136.

NENONEN, N. 2013. Analysing factors related to slipping, stumbling, and falling accidents at work: Application of data mining methods to Finnish occupational accidents and diseases statistics database. *Applied ergonomics,* 44**,** 215-224.

OERBEKKE, M. S., STUKSTETTE, M. J., SCHÜTTE, K., DE BIE, R. A., PISTERS, M. F. & VANWANSEELE, B. 2017. Concurrent validity and reliability of wireless instrumented insoles measuring postural balance and temporal gait parameters. *Gait & posture,* 51**,** 116-124.

PAI, Y.-C. & PATTON, J. 1997. Center of mass velocity-position predictions for balance control. *Journal of biomechanics,* 30**,** 347-354.

PAL, M., MAJUMDAR, D., DHARA, P. & MAJUMDAR, D. 2007. Cardiorespiratory responses of military load carriage with varying walking speeds and gradients. *Indian J Biol Sci,* 13**,** 1-9.

PALUMBO, N., GEORGE, B., JOHNSON, A. & CADE, D. 2001. The effects of backpack load carrying on dynamic balance as measured by limits of stability. *Work (Reading, Mass.),* 16**,** 123-129.

PARIJAT, P. & LOCKHART, T. E. 2008. Effects of lower extremity muscle fatigue on the outcomes of slip-induced falls. *Ergonomics,* 51**,** 1873-1884.

PATTERSON, K. K., GAGE, W. H., BROOKS, D., BLACK, S. E. & MCILROY, W. E. 2010a. Changes in gait symmetry and velocity after stroke: a cross-sectional study from weeks to years after stroke. *Neurorehabilitation and Neural Repair,* 24**,**

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

783-790.

PATTERSON, K. K., GAGE, W. H., BROOKS, D., BLACK, S. E. & MCILROY, W. E. 2010b. Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization. *Gait & posture,* 31**,** 241-246.

PHAN-BA, R., CALAY, P., GRODENT, P., DELRUE, G., LOMMERS, E., DELVAUX, V., MOONEN, G., NAGELS, G. & BELACHEW, S. 2012. A corrected version of the Timed-25 Foot Walk Test with a dynamic start to capture the maximum ambulation speed in multiple sclerosis patients. *NeuroRehabilitation,* 30**,** 261-266.

PIETILÄ, J., MEHRANG, S., TOLONEN, J., HELANDER, E., JIMISON, H., PAVEL, M. & KORHONEN, I. 2017. Evaluation of the accuracy and reliability for photoplethysmography based heart rate and beat-to-beat detection during daily activities. *EMBEC & NBC 2017.* Springer.

PLAMONDON, A., DENIS, D., DELISLE, A., LARIVIÈRE, C., SALAZAR, E. & GROUP, I. M. R. 2010. Biomechanical differences between expert and novice workers in a manual material handling task. *Ergonomics,* 53**,** 1239-1253.

POSADA-QUINTERO, H. F. & CHON, K. H. 2020. Innovations in electrodermal activity data collection and signal processing: A systematic review. *Sensors,* 20**,** 479.

QU, X., XIE, Y., HU, X. & ZHANG, H. 2020. Effects of fatigue on balance recovery from unexpected trips. *Human factors,* 62**,** 919-927.

QU, X. & YEO, J. C. 2011. Effects of load carriage and fatigue on gait characteristics. *Journal of biomechanics,* 44**,** 1259-1263.

RAMADAN, M. Z., KHALAF, T. M., RAGAB, A. M. & ABDELGAWAD, A. A. 2018. Influence of Shopping Bags Carrying on Human Responses While Walking. *Journal of healthcare engineering,* 2018.

REFAI, M. I. M., VAN BEIJNUM, B.-J. F., BUURKE, J. H. & VELTINK, P. H. 2018. Gait and dynamic balance sensing using wearable foot sensors. *IEEE transactions on neural systems and rehabilitation engineering,* 27**,** 218-227.

REIMER, B. & MEHLER, B. 2011. The impact of cognitive workload on physiological arousal in young adult drivers: a field study and simulation validation. *Ergonomics,* 54**,** 932-942.

RODRIGUEZ, F. S., SPILSKI, J., HEKELE, F., BEESE, N. O. & LACHMANN, T. 2019. Physical and cognitive demands of work in building construction. *Engineering, Construction and Architectural Management*.

SAFETY, N. I. F. O. & GROUP, H. B. B. W. 1994. *Workplace use of back belts: Review and recommendations*, US Department of Health and Human Services, Public Health Service, Centers ….

SATO, K. & DOBSON, R. L. 1970. Regional and individual variations in the function of the human eccrine sweat gland. *Journal of Investigative Dermatology,* 54**,** 443-449.

SAWKA, M. N., WENGER, C. B. & PANDOLF, K. B. 2010. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. *Comprehensive physiology***,** 157-185.

SCHAUB, K. 2006. Ergonomics of manual handling–Part 1: lifting and carrying. *Handbook on standards and guidelines in ergonomics and human factors***,** 254-269.

SCHOLZ, J. P., MILLFORD, J. P. & MCMILLAN, A. G. 1995. Neuromuscular coordination of squat lifting, I: effect of load magnitude. *Physical therapy,* 75**,** 119-132.

SCOTT, K. A., FISHER, G. G., BARON, A. E., TOMPA, E., STALLONES, L. & DIGUISEPPI, C. 2018. Same-level fall injuries in US workplaces by age group, gender, and industry. *American journal of industrial medicine,* 61**,** 111-119.

SIMPSON, K. M., MUNRO, B. J. & STEELE, J. R. 2011. Effect of load mass on posture, heart rate and subjective responses of recreational female hikers to prolonged load carriage. *Applied ergonomics,* 42**,** 403-410.

SOULE, R. G. & GOLDMAN, R. F. 1969. Energy cost of loads carried on the head, hands, or feet. *Journal of Applied Physiology,* 27**,** 687-690.

STATISTICS, B. O. L. 2016. Census of fatal occupational injuries. *Washington, DC: Bureau of Labor Statistics*.

STÖGGL, T. & MARTINER, A. 2017. Validation of Moticon's OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements. *Journal of sports sciences,* 35**,** 196-206.

STUEMPFLE, K. J., DRURY, D. G. & WILSON, A. L. 2004. Effect of load position on physiological and perceptual responses during load carriage with an internal frame backpack. *Ergonomics,* 47**,** 784-789.

TAMURA, T., MAEDA, Y., SEKINE, M. & YOSHIDA, M. 2014. Wearable photoplethysmographic sensors—past and present. *Electronics,* 3**,** 282-302.

TEASDALE, N., STELMACH, G. E. & BREUNIG, A. 1991. Postural sway characteristics of the elderly under normal and altered visual and support surface conditions. *Journal of Gerontology,* 46**,** B238-B244.

TIAN, Z., ZHU, N., ZHENG, G. & WEI, H. 2011. Experimental study on physiological and psychological effects of heat acclimatization in extreme hot environments. *Building and Environment,* 46**,** 2033-2041.

TSENG, H.-Y. & LIU, B.-S. 2011. Effects of load carrying methods and stair slopes on physiological response and postures during stairs ascending and descending.

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

Industrial health, 49**,** 30-36.

UMER, W., ANTWI-AFARI, M. F., LI, H., SZETO, G. P. & WONG, A. Y. 2018a. The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis. *International archives of occupational and environmental health,* 91**,** 125-144.

UMER, W., LI, H., LU, W., SZETO, G. P. Y. & WONG, A. Y. 2018b. Development of a tool to monitor static balance of construction workers for proactive fall safety management. *Automation in Construction,* 94**,** 438-448.

UMER, W., LI, H., SZETO, G. P. Y. & WONG, A. Y. 2018c. Proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures. *Journal of Construction Engineering and Management,* 144**,** 04018010.

VERJANS, M., DE BROECK, V. & EECKELAERT, L. 2007. *OSH in figures: young workers: facts and figures*, European Communities.

ZHANG, M. 2014. *Association between fatigue and safety performance of construction workers.* PhD dissertation, Tsinghua University.

ZULTOWSKI, I. & ARUIN, A. 2008. Carrying loads and postural sway in standing: the effect of load placement and magnitude. *Work,* 30**,** 359-368.

Anwer S, Li H, Antwi-Afari MF, Umer W, Mehmood I, Wong AYL. Effects of load carrying techniques on gait parameters, dynamic balance, and physiological parameters during a manual material handling task. Engineering, Construction and Architectural Management, 2021 (Accepted). DOI 10.1108/ECAM-03-2021-0245

Table 1. Demographic details of participants (*n = 15*)

Variables	**Mean (SD)**	**Range (min - max)**
Age, Y	31.5 (2.6)	10 (28 – 38)
Weight, kg	68.3 (3.1)	10 (65 – 75)
Height, m	1.7 (0.1)	0.2 (1.6 – 1.8)
BMI, kg/m^2	24.2 (0.7)	2.3 (23.1 – 25.4)
Shoe size (European)	40.2 (1.5)	5 (38 – 43)
Foot length, cm	25.2 (0.9)	3 (24 – 27)
Foot width, cm	9.5 (0.2)	0.7 (9.2 – 9.9)

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Table 2. Gait parameters during different load carrying techniques

Variables	**No Load (A)**	**Load in hands (B)**	**Load on the head (C)**	**Load on the predominant shoulder (D)**	**ANOVA**		**Effect size**	**Post-hoc analyses using Bonferroni corrections**					
					F	P	Partial eta-squared (η2)	A vs B	A vs C	A vs D	B vs C	B vs D	C vs D
Gait speed (m/s)	1.2 (0.04)	1.02 (0.11)	0.82 (0.12)	0.78 (0.09)	78.14	0.001*	0.85	0.18*	0.38*	0.42*	0.20*	0.24*	0.04
Cadence (strides/m)	51.3 (1.1)	51.7 (0.9)	46.5 (1.2)	47.4 (1.4)	5.82	0.002*	0.29	.43	4.83	3.92	5.25*	4.34	.909
Double support time (s)	0.05 (0.01)	0.20 (0.03)	0.30 (0.03)	0.28 (0.03)	38.39	0.001*	0.73	0.15*	0.25*	0.23*	0.10*	0.08	0.02
SR-Step duration	1.03 (0.02)	1.04 (0.03)	1.06 (0.05)	1.10 (0.04)	7.79	0.001*	0.36	0.01	0.03	0.07*	0.02	0.06*	0.03
SR-Stance duration	1.03 (0.01)	1.05 (0.02)	1.08 (0.06)	1.11 (0.06)	9.75	0.001*	0.41	0.02	0.05	0.08*	0.03	0.06*	0.03
SR-Swing duration	1.02 (0.01)	1.04 (0.02)	1.09 (0.06)	1.11 (0.13)	6.49	0.013*	0.32	0.02	0.07*	0.09*	0.05*	0.07*	0.02

Note: *The mean difference is significant at the 0.05 level; SR: Symmetric Ratio

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Table 3. Balance parameters during different load carrying techniques

Variables	**No Load (A)**	**Load on hand (B)**	**Load on head (C)**	**Load on shoulder (D)**	**ANOVA**		**Effect size**	**Post-hoc analyses using Bonferroni corrections**					
					F	P	Partial eta-squared (η2)	A vs B	A vs C	A vs D	B vs C	B vs D	C vs D
COP (AP)-L (mm)	11.03 (4.60)	-5.10 (14.64)	21.10 (11.69)	17.47 (0.78)	20.792	0.001*	0.72	16.13*	10.07	6.43*	26.20*	22.57*	3.63
COP (AP)-R (mm)	-4.13 (1.38)	-4.17 (11.43)	-0.63 (2.85)	-9.40 (5.99)	2.275	0.153	0.22	-	-	-	-	-	-
COP (ML)-L (mm)	-2.10 (1.08)	-3.37 (1.36)	-1.53 (1.61)	-0.57 (0.72)	8.119	0.010*	0.50	1.27	0.57	1.53	1.84*	2.80*	0.96
COP (ML)-R (mm)	-4.27 (0.28)	-4.50 (1.29)	-2.80 (0.61)	-4.30 (0.53)	11.866	0.002*	0.60	0.23	1.47*	0.03	1.70*	0.20	1.50*
COP velocity-L (mm/sec)	277.13 (6.53)	224.60 (55.96)	253.93 (32.54)	251.03 (6.54)	3.685	0.083	0.32	-	-	-	-	-	-
COP velocity-R (mm/sec)	342.20 (57.04)	236.53 (26.72)	259.76 (35.32)	258.17 (17.95)	15.124	0.004*	0.65	105.67*	82.43*	84.03*	23.23	21.63	1.60

Note: *The mean difference is significant at the 0.05 level; COP, Center of pressure; AP, Anteroposterior; ML, Mediolateral; L, Left; R, Right

Table 4. Comparisons of balance parameters between stable and unstable surfaces

Load carrying techniques	**Balance parameters**	**Stable surface (Floor)**	**Unstable surface (Foam)**	**ANOVA**	
				F	P
No Load	COP (AP)- (mm)	-7.22 (10.67)	3.45 (2.02)	2.073	0.223
	COP (ML)- (mm)	-4.02 (1.36)	-3.18 (0.76)	0.861	0.406
	COP velocity- (mm/sec)	278.08 (46.66)	309.67 (34.74)	0.884	0.400
Load in hands	COP (AP)- (mm)	0.88 (4.23)	-4.63 (12.78)	0.387	0.568
	COP (ML)- (mm)	-3.33 (0.67)	-3.93 (1.30)	0.501	0.518
	COP velocity- (mm/sec)	344.32 (23.01)	230.57 (47.73)	13.828	0.020*
Load on head	COP (AP)- (mm)	3.30 (10.32)	10.23 (7.38)	0.309	0.608
	COP (ML)- (mm)	-2.75 (1.79)	-2.17 (1.12)	0.228	0.658
	COP velocity- (mm/sec)	280.62 (60.51)	256.85 (36.33)	0.340	0.591
Load on shoulder	COP (AP)- (mm)	6.47 (2.43)	4.03 (3.38)	1.025	0.369
	COP (ML)- (mm)	-1.90 (1.75)	-2.43 (0.72)	0.237	0.652
	COP velocity- (mm/sec)	284.42 (19.63)	254.60 (22.09)	11.165	0.029*

Note: *Statistically significant at the 0.05 level; COP, Center of pressure; AP, Anteroposterior; ML, Mediolateral

Table 5. Physiological parameters (Heart rate and electrodermal activity) during different carrying techniques

Variables	**No Load (A)**	**Load in hands (B)**	**Load on head (C)**	**Load on shoulder (D)**	**ANOVA**		**Effect size**	**Post-hoc analyses using Bonferroni corrections**					
					F	P	Partial eta-squared (η2)	A vs B	A vs C	A vs D	B vs C	B vs D	C vs D
Heart rate (beats/m)	69.5 (1.18)	76.16 (3.06)	85.15 (3.63)	77.49 (1.66)	5.820	0.002*	0.29	6.7	15.7*	8.0*	8.98	1.33	7.65
Electrodermal activity (µS)	8.95 (0.30)	13.95 (1.27)	14.33 (1.13)	14.10 (1.17)	16.249	0.001*	0.54	5.00*	5.38*	5.15*	0.38	0.15	0.23

Note: *The mean difference is significant at the 0.05 level.

Table 6. Comparisons of load carrying approaches in the published literature

Citations	Load pattern	Outcome	Results	Conclusions/ Recommendations
Thakurta et al., 2017	No load Head load Hand load Shoulder load	Gait parameters	*Gait speed (m/s)* 4.8 ± 0.56 (No load); 4.0 ± 0.11 (Head load); 3.09 ± 0.23 (Hand load); 3.4 ± 0.10 (Shoulder load) *Cadence (steps per minute)* 107.66 ± 0.13 (No load); 114.97 ± 0.22 (Head load); 118.66 ± 0.41 (Hand load); 118.51 ± 0.16 (Shoulder load) *Double limb support (s)* 0.60 ± 0.04 (No load); 0.65 ± 0.19 (Head load); 0.91 ± 0.06 (Hand load); 0.71 ± 0.05 (Shoulder load)	Among the Indian manual construction workers, carrying a high load on the head showed the least variation from the regular gait pattern. While carrying load on the head offers a number of significant advantages over hand and shoulder loading, carrying load on the head might put undue strain on the neck muscles, resulting in mechanical neck pain.
McGill et al., 2013	Load in one hand Load in both hands	Spinal compressive loading, Maximum voluntary contraction (%)	*Shear force at L4/L5* 167 ± 113.2 (Load in both hands); 200 ± 109.6 (Load in one hand) *Maximum voluntary contraction (%)* Left back muscles: 2.7 ± 2.6 (Load in both hands); 7.8 ± 5.5 (Load in one hand) Right back muscles: 3.1 ± 2.1 (Load in both hands); 3.1 ± 1.7 (Load in one hand)	Carrying a load in two hands places a significantly lesser compressive load on the low back than carrying the load in one hand. During material carrying, it is advised to divide the load between both hands, and it should be considered when planning tasks to avoid musculoskeletal risk.

			Left abdominals: 3.7 ± 2.8 (Load in both hands); 8.3 ± 6.7 (Load in one hand) Right abdominals: 2.3 ± 0.8 (Load in both hands); 5.2 ± 3.2 (Load in one hand)	
Ramadan et al., 2018	Load in one hand Load in both hands	Cardiac cost, Percentage of maximum voluntary contraction (% MVC), Peak plantar pressure (PPP), Discomfort rating	*Cardiac cost* 13.1 ± 3.8 (Load in both hands); 16.7 ± 4.6 (Load in one hand) *Percentage of maximum voluntary contraction (% MVC)* lower (Load in both hands); higher (Load in one hand) *Peak plantar pressure (kPa)* ≈ 220 (load in both hands); ≈ 235 (load in one hand) *Discomfort rating* lower discomfort (Load in both hands); higher discomfort (Load in one hand)	Based on the observed physiological responses (lower cardiac cost and lower percent MVC) and subjective response (lower discomfort rating), the two-hand carrying approach is better over one-hand carrying. Carrying bags close to the body with both hands is recommended.
Das et al., 2012	No load Load in one hand Load in both hands	Gait parameters	*Cadence (steps per minute)* 87.1 (No load); 90.5 (Load in one hand); 87.9 (Load in both hands) *Step length (cm)*	Carrying a load in both hands yields better gait parameters compared to carrying a load in one hand.

			60.5 (No Load); 62.2 (Load in one hand); 60 (Load in both hands)	
Alamoudi et al., 2018	Load in one hand Load in both hands Posterior load Frontal load	Gait parameters	*Gait speed (m/s)* 1.12 ± 0.14 (No load); 1.11 ± 0.10 (Load in one hand); 1.12 ± 0.11 (Load in both hands); 1.12 ± 0.10 (Posterior load); 1.12 ± 0.11 (Frontal load) *Cadence (steps per minute)* 104.91 ± 6.68 (No load); 107.5 ± 7.69 (Load in one hand); 107.36 ± 7.46 (Load in both hands); 109.27 ± 7.65 (Posterior load); 110.83 ± 7.85 (Frontal load) *Double limb support (%)* 21.1 ± 2.4 (No load); 20.7 ± 2.4 (Load in one hand); 20.8 ± 2.4 (Load in both hands); 20.7 ± 2.1 (Posterior load); 21.2 ± 2.4 (Frontal load)	This study concluded that carrying load in one hand and forward loading caused most unstable gait compared to carrying load in both hands and posterior loading.
Current	No load	Gait parameters,	*Gait speed (m/s)*	Findings of this study suggest that

study	Head load Load in both hands Load on the dominant shoulder	Balance parameters, Heart rate (HR), Electrodermal activity (EDA)	1.2 ± 0.04 (No load); 0.82 ± 0.12 (Head load); 1.02 ± 0.11 (Hand load); 0.78 ± 0.09 (Shoulder load) *Cadence (strides per minute)* 51.3 ± 1.1 (No load); 46.5 ± 1.2 (Head load); 51.7 ± 0.9 (Hand load); 47.41 ± 1.4 (Shoulder load) *Double limb support (s)* 0.05 ± 0.01 (No load); 0.30 ± 0.03 (Head load); 0.20 ± 0.03 (Hand load); 0.28 ± 0.03 (Shoulder load) *SR-Step duration* 1.03 ± 0.02 (No load); 1.06 ± 0.12 (Head load); 1.04 ± 0.05 (Hand load); 1.10 ± 0.04 (Shoulder load) *SR-Stance duration* 1.03 ± 0.01 (No load); 1.08 ± 0.06 (Head load); 1.05 ± 0.02 (Hand load);	carrying loads in both hands yields better gait symmetry and dynamic balance than carrying loads on the dominant shoulder or head. All three load carrying techniques increased HR and EDA from baseline. Construction workers are recommended to carry loads in both hands, to improve their gait symmetry and dynamic balance and to lower their risk of falls.

1.11 ± 0.06 (Shoulder load)
SR-Swing duration
1.02 ± 0.01 (No load);
1.09 ± 0.06 (Head load);
1.04 ± 0.02 (Hand load);
1.11 ± 0.13 (Shoulder load)
COP velocity (mm/sec)
278.08 ± 46.66 (No load);
280.62 ± 60.51 (Head load);
344.32 ± 23.01(Hand load);
284.42 ± 19.63 (Shoulder load)
Hear rate (beats/minute)
69.5 ±1.18 (No load);
85.15 ±3.63 (Head load);
76.16 ±3.06 (Hand load);
77.49 ± 1.66 (Shoulder load)
Electrodermal activity (µS)
8.95 ± 0.30 (No load);
14.33 ± 1.13 (Head load);
13.95 ± 1.27 (Hand load);
14.10 ± 1.17 (Shoulder load)

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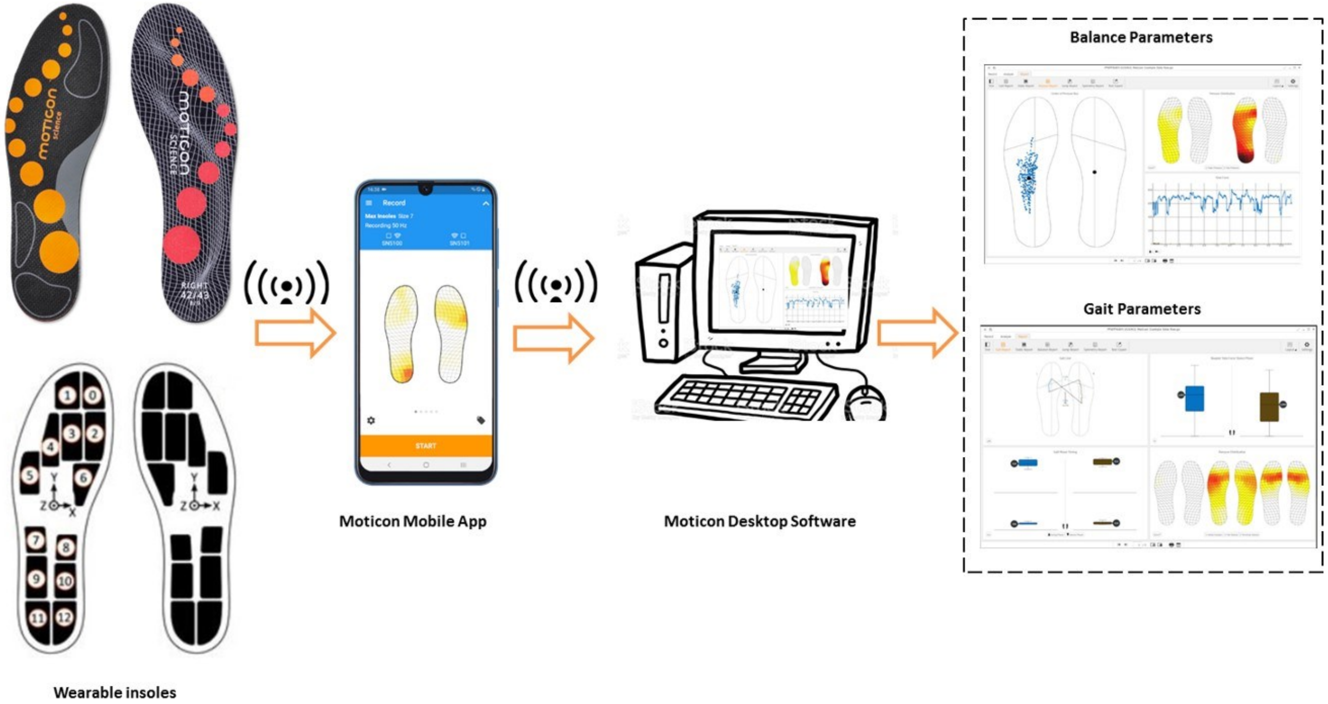

Figure 1. Overview of wearable insole pressure system

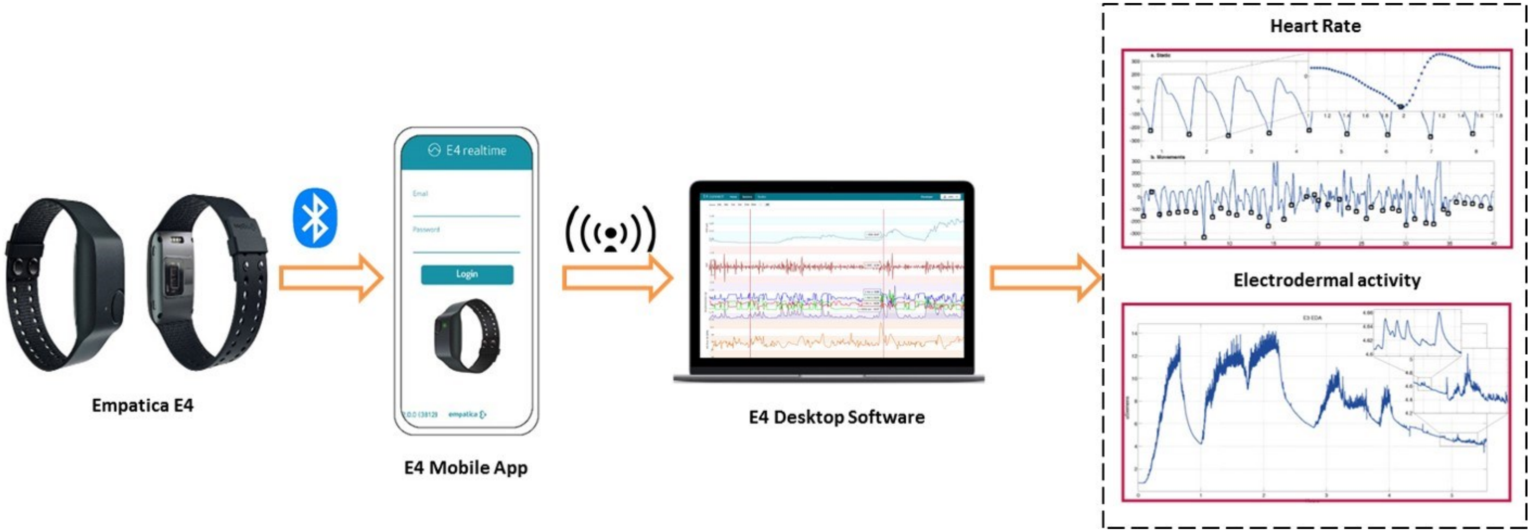

Figure 2. Overview of Photoplethysmography (PPG) wristwatch

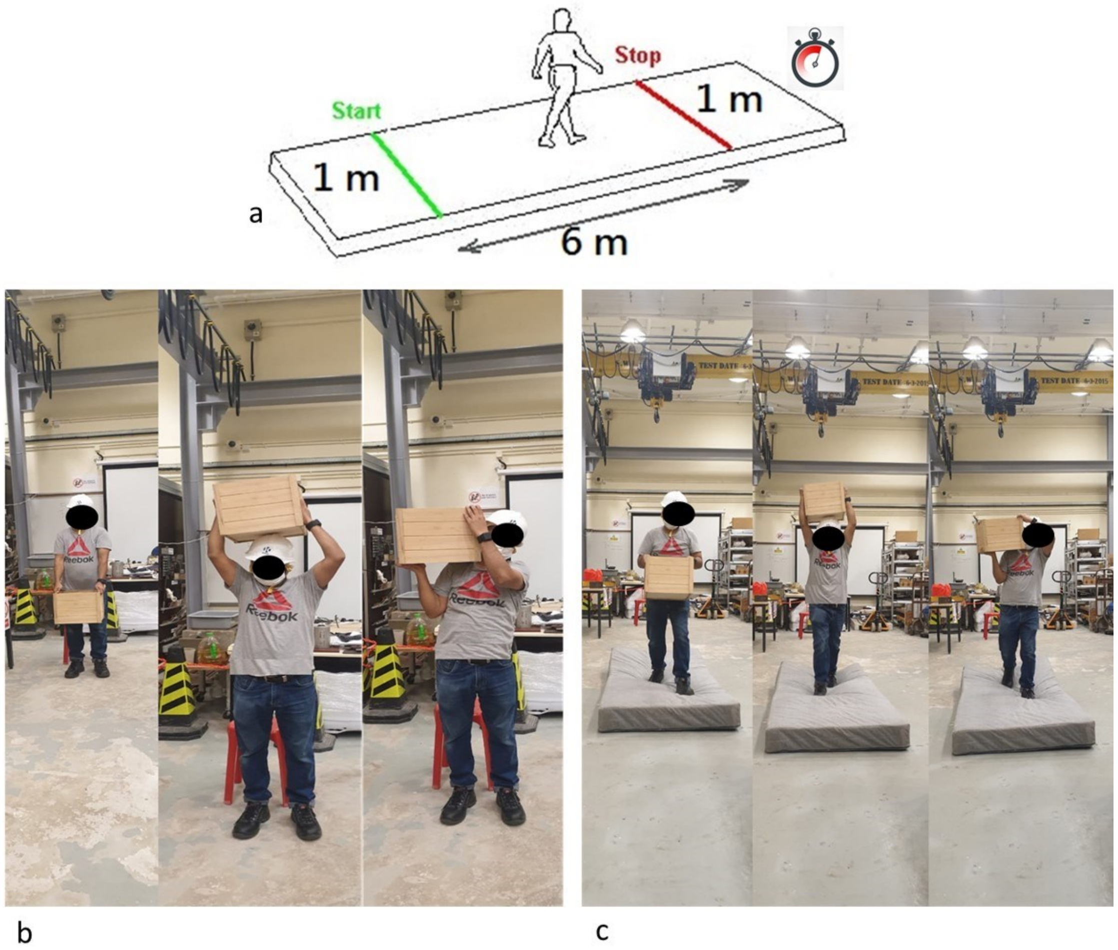

Figure 3. Experimental procedures: (a) illustration of an 8-m walkway; (b) different load carrying approaches during stable trials; (c) different load carrying approaches during unstable trials