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Quantifying the effect of mental stress on physical stress for construction tasks

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Abstract

Because of labor-intensive and physically demanding tasks, construction workers are known to be at a higher risk of developing physical fatigue. Recently, studies have shown that construction workers are often exposed to considerable mental stresses as well. While a number of studies have proposed methods and tools to measure and monitor physical and mental stress disjointedly, there is a need to explore their interaction. The literature indicates that no previous study has endeavored to evaluate the effect of mental stress on physical stress for construction tasks. This investigation is necessary to better comprehend work demands of construction tasks. Accordingly, entailing randomized crossover design and simulated manual material handling experiment, this study evaluated the effect of cognitive task-led mental stress on physical stress using both subjective (ratings of perceived exertion) and objective measures (heart rate, skin temperature and skin conductance). The results revealed that cognitive task-led mental stress led to a significant increase in subjective ratings of perceived exertion accompanied by an increase in skin temperature and skin conductance, while heart rate remained unaffected. The findings of this study add to the body of knowledge by highlighting that traditional benchmarking of task demands using only physiological measures may not be comprehensive. Rather, it might be suggested that additional psychological measurements are also essential as they might affect physical stress development. Furthermore, the current study has increased our understanding related to the interaction of physical and mental stress by revealing inter-individual differences among the participants. Accordingly, by examining each worker separately, practitioners and safety managers can develop better mitigation strategies and individualized training programs, especially for more vulnerable workers, which can enhance overall health and safety on construction jobsites.

Keywords

Construction safety; physical stress; mental stress; manual material handling task

Introduction

Construction is considered as one of the most hazardous industries around the globe and consequently, workers' health and safety records cast an overly gloomy picture with high turnover rates. A major underlying risk factor is the physically and mentally demanding nature of the construction tasks (The Chartered Institute of Building 2006). Many times, construction tasks are often performed in an outdoor environment, adversarial environmental conditions, for a prolonged duration, requiring repetitive and physically demanding sub-tasks (Yu et al. 2021). As such, numerous studies have highlighted high physical stress (i.e., sustained excessive physical exertion that leads to physical fatigue) among construction workers while working, which many times exceeds the physiological limits/standards (Hanklang et al. 2014; Meo et al. 2013; Techera et al. 2018; Zhang et al. 2015a). Working under excessive physical stress could have adverse effects in many ways. It has been linked with higher susceptibility to mistakes and errors, poor workmanship, lower productivity and more importantly, accidents (Aryal et al. 2017; Lee et al. 2017; Umer et al. 2020). Indeed, the association between physical stress and accidents has been well documented in the literature. For example, Chiang et al. (2018) investigated fatal accidents in the Hong Kong construction industry from 1995 to 2015, which found an increased rate of accidents in the periods, 'two-hours before lunch' and 'one-hour after lunch', attributed to physical stress and overexertion. Similarly, studies conducted in the building, and oil and gas industries found physical stress-related overexertion to be the leading cause of accidents and work-related injuries (Adane et al. 2013; Chan 2011).

Similarly, mental stress is also widely prevalent among construction workers (Boschman et al. 2013; Love et al. 2010; Petersen and Zwerling 1998). Mental stress can be defined as the coping response of a person when subjected to events or situations that challenge his/her psychological homeostasis (Yang et al. 2002). There are a number of factors that can cause mental stress among construction workers including but not limited to (1) work/task-related factors such as high cognitive demands of work tasks, working overtime, lack of personal protective equipment, fear of mistakes, time pressure, working in hazardous environment (Azeez et al. 2019; Burlet-Vienney et al. 2015; Wu et al. 2018), (2) management-related factors such as insufficient support from senior colleagues and management and unfair reward and treatment (Leung et al. 2015, 2012) and (3) interpersonal-related factors such as conflicts at workplace, poor co-worker support and work-family conflicts (Leung et al. 2015; Ng et al. 2005; Wu et al. 2018). Like physical stress, mental stress is also associated with numerous unfavorable outcomes such as health issues, reduced productivity, mistakes and errors, and injuries and accidents (Abbe et al. 2011; Leung et al. 2015; Li et al.

2019b, 2020). In the long run, mental stress could lead to many serious systemic illnesses such as cardiovascular disorders, stroke, depression, and other mental health illnesses. For instance, a previous study reported an increased risk of incident stroke in workers with high occupational mental stress (Tsutsumi et al. 2011). Similarly, other studies have reported a strong positive association between occupational mental stress and cardiovascular diseases in the working population (Belkic et al. 2004; Uchiyama et al. 2005; Yoshimasu 2001). Another study reported that high occupational mental stress causes an increase in risk of cardiovascular mortality among industrial workers (Kivimaki 2002). Furthermore, mental stress can advance the development of coronary heart disease and could contribute to the occurrence of cancer (Wang et al. 2007). Additionally, construction workers are more prone to develop psychological disorders such as mental occupational stress-related and emotional problems (Petersen and Zwerling 1998). The gravity of the situation can be understood by the fact that every year in the UK construction industry, 400,000 work hours are lost because of mental stress-related issues (PwC 2014). As such, high physical and mental stress are widely prevalent issues in the construction industry.

From management's perspective, it is often said that you cannot manage what you cannot measure (Cioffi 2006). Accordingly, though separately, monitoring physical and mental stress has been the focus of numerous studies for quite some time (Aryal et al. 2017; Chen et al. 2016; Jebelli and Lee 2018; Li et al. 2019a; Mitropoulos and Memarian 2013; Ueno et al. 2018; Umer et al. 2020). Initially, interviews or questionnaires as data measurement tools had been used for this purpose. However, with the advancement in sensor technologies, physiological and psychological measures such as heart rate, breathing frequency, skin temperature, energy expenditure, heart rate variability, electrodermal activity, and electroencephalograph have been used to objectively measure physical and mental stress (Anwer et al. 2021). While such approaches have deepened our understanding related to physical and mental stress, studies investigating their interaction in the construction industry have been scarce. Specifically, how acute mental stress affects the physical stress of construction workers remains unexplored. Moreover, it is worthwhile to explore that if there is an interaction between physical and acute mental stress, whether the interaction is at only perception level or there are physiological manifestations too (i.e., change in heart rate, breathing rate or skin temperature because of the acute mental stress). These research gaps need to be unveiled to better comprehend the psychophysiological needs to ensure the health and safety of the construction workers. This could help (1) managers to prevent workers from suffering extreme stress, (2) better design interventions for stress management and (3) effective policy-making based on evidence-based information. To explore a part of the aforementioned knowledge gaps, this study conducted an experimental study comprising of manual material handling tasks to test whether acute mental stress affects physical stress or not. Specifically, physical stress development was compared using ratings of perceived exertion (RPE) scale (a subjective measure) between a physical stress task and a task entailing both mental and physical stress. Moreover, the comparison between the tasks was also conducted for the objective measures which included heart rate, skin temperature and skin conductance. Finally, variation in the subjective ratings of physical exertion for the two tasks were compared across the participants to comprehend and evaluate inter-individual differences.

Literature review

Traditionally, questionnaires were the primary data measurement tool used to assess physical and mental stress in occupational settings. Worth mentioning, most of these questionnaires covered dimensions of both physical and mental stress. A very common example of such data measurement tool is NASA Task Load Index (TLX) questionnaire. It encompasses six different dimensions of workload including physical and acute mental stress. Studies such as Mitropoulos and Memarian (2013) made use of NASA TLX questionnaire to investigate the task demands of the masonry work. Similarly, Hsu et al. (2008) utilized RCIF (Research Committee on Industrial Fatigue) scale by Japan Society for Occupational Health to investigate the physical and mental demands of work among high-rise building construction workers. Likewise, many other generic questionnaires exist that could be used for this purpose. However, some researchers argue that each questionnaire is designed for a particular purpose, in a certain context, and targets a specific population. Considering the constraints of the construction industry (e.g., dynamic working conditions, prolonged work shifts, awkward postures and heavy workload), some researchers have argued for construction industry-specific workload/fatigue assessment tools. Accordingly, Zhang et al. (2015b) developed and validated a 10-item questionnaire to investigate both the physical and mental fatigue of construction workers.

Unlike questionnaires which have been used to monitor both dimensions of stress (i.e., physical and mental), objective measurements have been used to monitor either of them, at a time. For physical stress monitoring, researchers have used heart rate, skin temperature, electromyography (EMG), oxygen consumption and jerk metrics either individually or collectively, for passive/descriptive or pro-active/predictive analysis. Bird’s eye view of these studies indicates that heart rate is the most commonly used metric to indicate physical stress among construction workers. For example, Gatti et al. (2014) and Ueno et al. (2018) measured the heart rate of the construction workers to descriptively analyze the relation between physical stress and heart rate. Generally, a relative increase in heart rate indicates increased physical stress because of the higher demands of the work tasks or environmental conditions.

Skin temperature is also reported to be strongly linked to physical stress and fatigue. Chan et al. (2012) found an increase in ear lobe temperature with an increase in physical stress and exhaustion. Similarly, Umer et al. (2020) found that heightened physical exertion was related to an increase in skin temperature measured at serratus anterior muscles. Conversely, Aryal et al. (2017) found a decrease in skin temperature at different face parts with an increase in physical stress. More importantly, Aryal et al. (2017) and Umer et al. (2020) found skin temperature to be a better predictor of physical stress than other physiological measurements such as heart rate. Besides, many studies have also studied EMG signals to identify physical stress for construction activities. Unlike other physiological metrics, EMG provides localized physical stress analysis for a certain body part/muscle group. Usually, an increase in amplitude root mean square and a decrease in median frequency indicate heightened physical stress. Accordingly, many previous studies have used these EMG metrics to investigate physiological demands of repetitive manual material handling, roofing and rebar tying tasks (Antwi-Afari et al. 2017, 2018; Umer et al. 2017a; b; Wang et al. 2015).

Numerous studies have also explored oxygen consumption to assess physical stress among construction workers. Generally, increased oxygen consumption is associated with higher task demands and physical stress. Li et al. (2009) and Wong et al. (2014) measured oxygen consumption, whereas, Abdelhamid and Everett (2002) monitored both heart rate and oxygen consumption for different trade workers and different tasks. These studies concluded that oxygen consumption could be used to monitor physical stress arising from different trade tasks.

Unlike the aforementioned studies, which majorly relied on physiological measures to monitor physical stress for construction tasks, few studies have explored mechanistic metrics such as jerk as an alternative approach. Studies by Sedighi Maman et al. (2017) and Zhang et al. (2019) conducted laboratory experiments to show that with an increase in physical stress, workers adjust their way of working and body movements which could be detected by measuring jerk metrics at various body parts.

For acute mental stress monitoring, EEG has been the most common tool in construction studies. EEG sensors use an array of sensing units placed on the head and forehead to observe the electrical activity of various parts of the brain. Chen et al. (2016) presented a framework to enable EEG data quantification to evaluate hazards through neural time–frequency analysis. Results indicated that their framework was capable to detect mentally stressful instances. Jebelli et al. (2018) found that wearable EEG can detect mental stress with an accuracy of up to 80% on construction sites. More recently, Li et al. (2019a) proposed pre-service mental fatigue screening of construction workers using spectral analysis of EEG data. Contrarily to the aforementioned studies which used EEG signals to detect mental stress, Jebelli et al. (2019) used physiological data comprising of photoplethysmogram, skin temperature, electrodermal activity and machine learning algorithms. This approach required only a single wrist band to be worn which is more pragmatic than EEG-based data collection which requires multiples sensors to be in firm contact at various places on the head of a worker.

Knowledge Gap

While the aforementioned studies have enabled us to quantify physical and acute mental stress among construction workers, there is a need to explore the interaction of physical and acute mental stress to better comprehend the demands of construction tasks and mitigate them. Recently, Xing et al. (2020) found that physical fatigue during manual material handling could significantly exacerbate mental stress. However, to the authors' knowledge, no study in the construction industry has investigated the effect of acute mental stress on physical stress. Although some studies in the non-construction domains have explored this interaction and found higher perceived exertion in presence of mental stress without affecting physiological variables (Van Cutsem et al. 2017a), at least a couple of issues necessitate such studies to be conducted in the domain of the construction industry. First, none of these studies explored specific construction tasks such as manual material handling. Different work tasks may lead to different results while evaluating the effect of mental stress on physical stress. For example, rowing and rebar tying in squatting posture, both are known to induce low-back fatigue, however, surface electromyography (sEMG) for both of these activities showed a significant decrease in median frequency of sEMG signals (an objective measure of peripheral fatigue) for rowing only (Caldwell et al. 2003), but not for rebar tying (Umer et al. 2017b). Second, previous studies did not evaluate the change of skin temperature because of mental stress induction. Skin temperature might be an excellent objective indicator of mental stress-induced change in physical stress because recent studies (Aryal et al. 2017; Umer 2020; Umer et al. 2020) have found skin temperature to be highly related to an increase in physical exertion/fatigue. Accordingly, this study aims to quantify the changes in subjective and objective indicators of physical stress as a consequence of mental stress. While there could be multiple factors that could cause mental stress among construction workers including (1) work/task-related factors, (2) management-related factors, and (3) interpersonal related factors as discussed earlier, this study has focused on prolonged cognitive task as a mental stressor because recent research has found that construction workers suffer from higher cognitive workload as compared to workers in other industries (Azeez et al. 2019). Also, the cognitive workload of construction workers is expected to increase further in the coming years due to the ongoing digitization of the construction industry (Rodriguez et al. 2019). Last but not the least, other stressors such as working in hazardous environment and time-pressure may fail to induce mental stress under simulated environment when the participants know that it is just a simulation.

Methods

Participants

For the study, eight participants having an age between 18 and 40 years took part in the experiments. To be eligible for participation in the study, participants had to be free from pulmonary, cardiac, musculoskeletal, and psychological disorders. Prior to data collection, the experimentation along with the purpose was explained to the participants and their consent was sought.

Procedure

[Figure 1]

This study adopted a randomized crossover study design spanning over two days (Fig. 1). The participants were asked to participate in the experiments on two separate days to avoid carryover effects which may confound the results, if the experiments are conducted in a single day. On each day, the participants were first equipped with the sensors as explained in the following section (i.e., Instrumentation). Afterwards, the participants rested for ten minutes while their baseline physiological measures were recorded. These baseline measures were used as a reference for further analysis for each participant. Then, the participants were randomly assigned to either a mental stress task or a non-stress task. The mental stress task required the participants to transform a four-digit number while sitting for a total duration of 25 minutes at a self-selected pace (Kahneman 1973). The participants heard a series of four digits (e.g., 4906) and were then asked to respond with the transformation of that four-digit number of that series by adding one to each digit of the original number (i.e., 5017). The process was continued until the prescribed time elapsed. Afterwards, the participants were asked to perform a manual material handling task involving carrying a 15kg backpack for 25 continuous minutes (around a large table, 4.3 by 2.7m, Fig. 2) while the mental stress task also continued simultaneously. Every five minutes, the participants were requested to describe their perception of perceived exertion using Borg-20 scale. Borg-20 has been tested in various domains and has been found a valid and reliable tool to solicit physical stress among different working populations (Carvalho et al. 2009; Day et al. 2004; Wilson and Jones 1991).

Whereas the non-stress task entailed watching a documentary named "World Class Trains – The Venice Simplon Orient Express" for a duration of 25 minutes. The documentary is known to be emotionally neutral and research has indicated that watching it does not induce any mental stress (Duncan et al. 2015; O'Keeffe et al. 2020). After watching the documentary, the participants were asked to perform the same manual material handling task as explained above. However, in this case, the participants were not exposed to mental stress task. Afterwards, the sensors were removed and participants were let free to leave.

[Figure 2]

Instrumentation

To monitor objective measures of physical and mental stress, the participants were asked to wear an Equivital vest (model EQ02 LifeMonitor, Fig. 3). This device has been reported as valid and accurate equipment to measure various physiological metrics (Akintola et al. 2016; Liu et al. 2013). The vest was equipped with electrocardiography (ECG) electrodes to monitor heart rate and skin temperature sensor. Additionally, the vest allowed connecting electrodes of electrodermal activity (EDA) which is considered as an objective indicator of mental stress. The electrodes were placed at the palms of the hands because it is reported to be one of the most sensitive and suitable body landmarks for the collection of EDA signals (van Dooren et al. 2012).

[Figure 3]

Data Analysis

To evaluate the impact of mental stress on physical stress, a two-way repeated-measures analysis of variance (ANOVA) was conducted to assess the impact of stress and time on the perception of physical exertion. Because of different subsequent tests for normal and non-normal data, Shapiro-Wilk test was used to assess the normality. The results found that the ratings of perceived exertion (RPE) data was non-normal. Accordingly, significant results were further explored using Wilcoxon signed-rank tests. For statistical tests, significance was set at $p<0.05$. For comparing heart rate, skin temperature and skin conductance, the respective values for the preceding five minutes were averaged and normalized using baseline measurements for each participant. Then, for each experimental condition, average data for different time periods were combined and compared without conducting statistical test. Furthermore, to evaluate the inter-individual variability for the interaction of physical and mental stress, ratings of physical exertion at the end of both experimental conditions for each participant were visually inspected.

Results

Ratings of perceived exertion results for both experimental conditions are shown in Fig. 4. Statistical analysis revealed a significant impact of time and experimental conditions, however, the interaction between the two factors was insignificant (Table 1). Wilcoxon signed-rank tests revealed that mean differences between exertion levels for the two experimental conditions were statistically significant from time period of 10 to 15 min and onwards. Moreover, a trend of increasing mean difference with time was observed. Specifically, the mean difference of physical exertion after five minutes of manual material handling task was 1.4 (95% CI = 0.36 to 2.52) whereas at the end of the task, it was 1.85 (95% CI = 1.08 to 4.16) on Borg-20 scale.

[Table 1]

[Figure 4]

Comparison for normalized heart rate showed no substantial difference between the two experimental conditions (mean normalized heart rate was 1.20 for both conditions, Fig. 5). Overall, manual material handling task led to an elevated heart rate as compared to the rest condition (i.e., normalized heart rate varied from approximately 1.16 to 1.23). While comparing different time periods, only the time period of 0 to 5 min tended to show a relatively higher normalized heart rate for mentally stressed condition in comparison with the non-stressed condition, during manual material handling task. In contrast to heart rate, normalized skin temperature and normalized skin conductance revealed higher values for mentally stressed condition as compared to non-stressed condition. Specifically, the mean difference between stressed and non-stressed condition for normalized skin temperature was 0.02 (Fig. 6). For non-stressed mental experimental condition, the mean normalized skin temperature for different time periods varied between 1.08 and 1.11 whereas the same for mentally stressed condition varied between 1.10 and 1.13. Additionally, the increase in normalized skin temperature associated with mental stress was very similar across different time periods. Specifically, this increase was computed to be around 0.02 on a normalized scale.

Similarly, notable difference for normalized skin conductance between the two experimental conditions was observed. Specifically, mentally stressed condition led to larger normalized skin conductance values with a mean difference of 0.34 (Fig. 7). For mentally non-stressed condition, mean value for different time periods varied between 1.3 and 1.7, whereas for the stressed condition, normalized skin conductance values tended to converge between values of 1.8 and 1.9.

[Figure 5]

[Figure 6]

[Figure 7]

Ratings of perceived exertion (RPE) at the end of both experimental conditions for each participant are shown in Fig. 8. RPE varied more among the participants for mentally non-stressed condition as compared to stressed condition (RPE standard deviation for the former was 2.39, whereas, for the latter, it was 0.84). Specifically, mean RPE score for the non-stressed condition was 15.5 with minimum and the maximum values of 12 and 18, respectively. On the other hand, the mean value for the stressed condition was 18.1 with a minimum value of 17 and a maximum value of 19.

[Figure 8]

Discussion

While previous studies have focused on identifying and monitoring physical and mental stress independently, this study for the first time evaluated the impact of cognitive task-led mental stress on physical exertion for construction tasks. The results indicate that cognitive task-led mental stress led to significantly increased perception of physical exertion which was accompanied by increase in mean skin temperature and mean skin conductance. The increase in perception of physical exertion because of mental stress is in accordance with the studies conducted in the non-construction domain such by Van Cutsem et al. (2017) and Mehta and Parasuraman (2014). Regarding skin temperature, in the authors’ opinion, none of the previous work has studied it to evaluate the interaction of physical and mental stress, specifically for construction tasks. The results of this study have highlighted that increase in perceived physical exertion because of cognitive task-led mental stress is accompanied by an increase in normalized skin temperature without variation in normalized heart rate. While previous studies focusing only on physical exertion (Aryal et al. 2017; Umer 2020; Umer et al. 2020) have reported better capability of skin temperature to discern physical exertion levels as compared to heart rate, the current study suggests that skin temperature may perhaps also better differentiate physical stress and combined physical and mental stress. Accordingly, future studies evaluating physical, mental stress or their combination are recommended to incorporate skin temperature measurement in their studies. Besides, skin conductance is considered to be an objective indicator of mental stress. Accordingly, this study also found skin conductance to be higher for mentally stressed condition. The results also indicate that for physical exertion tasks without mental stress, there was an increase in skin conductance (Fig. 7), which indicates a correlation between physical exertion and skin conductance as well. More importantly, ceiling effect for skin conductance can be observed for tasks that involved a combination of physical and cognitive task-led mental stress (Fig. 7). Specifically, average normalized skin conductance values were around 1.8 and 1.9 for all participants, irrespective of the physical exertion level. Future studies should further explore relation between the skin conductance and physical exertion as well as the observed ceiling effect for normalized skin conductance values.

In contrast, the results demonstrate that mental stress did not lead to an increase in mean heart rate while performing manual material handling task as compared to non-stressed condition. These results are in accordance with previous non-construction studies (e.g. Pageaux et al. 2015). A close examination of Fig. 5 may help comprehend this phenomenon. It is known that while resting, mental stress leads to an increase in heart rate (Taelman et al. 2008). This is also evident in this study for the first five minutes where an increase in heart rate can be observed (Fig. 5). However, as physical exertion becomes intense as a consequence of extended duration, mental stress-induced increase in heart rate became insignificant because of already high autonomic activation and exercise pressor reflex led by physical exertion (Marcora et al. 2009). Resultantly, for the remaining time duration, no further mental stress led to an increase in heart rate was observed.

Individualized post-hoc analysis for ratings of perceived exertion reveals interesting observations. Fig. 8 illustrates individual RPE scores at the end of the experiments. It can be seen that the impact of cognitive tasks-led mental stress on physical exertion was not the same across the participants. Some of them (e.g. Participant number 1, 4 and 6) depicted only a slight increase in RPE whereas, for some, the increase was much larger. Specifically, Participant 2 and Participant 5 showed an increase of five units on RPE scale whereas the same for Participant 8 was four. This inter-individual variation underpins that besides exploring the group effect, there is a need to explore the effect of physical and mental stress at the individual level also. This could help at least in a couple of ways. First, it might assist in identifying the individuals who are more prone to rapid development of physical exertion in presence of mental stress. This could enable the deployment of more resilient workers to work environments that entail both physical and mental stress. Secondly, such evaluation seems to be useful in evaluating customized training programs dedicated to vulnerable workers.

This study has important implications for physiological benchmarking of construction activities, safety planning and physical stress associated hazards. For example, numerous studies have endeavored to quantify the physiological cost of various construction tasks and trades (Abdelhamid and Everett 2002; Gatti et al. 2014; Li et al. 2009; Ueno et al. 2018; Wong et al. 2014). However, these studies primarily focused on physical stress and fatigue without considering mental stress. Considering the results of this study in view, it is quite possible that in presence of mental stress, physical stress may aggravate, leading to heightened physical demands and associated hazards. Therefore, researchers and industry practitioners may consider further exploring this interaction between physical and mental stress for comprehensive benchmarking of task demands instead of wholly relying on the results of the aforementioned studies only. Similarly, safety managers, superintendents and foremen could be conservative while working out work-rest schedules in circumstances where mental stress is also present. Also, given the interindividual variability found in this study, they may monitor individual workers using appropriate tools to proactively identify workers more susceptible to increased physical stress in presence of mental stress. This will help in developing individualized training programs for these individuals and deploying more resilient workers wherever deemed necessary. Besides, the interaction of mental and physical stress may influence physical stress associated hazards also. For example, it is well understood that sustained physical stress and fatigue can compromise the balance of the construction workers which might lead to fall accidents (Hsiao and Simeonov 2001; Umer et al. 2018b; a). Hypothetically, mental stress might further impair the balance of already physically fatigued construction workers. Accordingly, future studies should investigate the worsening of construction workers' balance under both conditions, physical fatigue only and physical fatigue together with mental stress.

Limitations and future work

The results of this study have highlighted that cognitive task-led mental stress may elevate physical stress for construction tasks. Despite the contributions, the study had limitations that should be acknowledged. First, the study used limited non-construction participants in an indoor simulated environment. Therefore, future studies should verify the results of this study on a large number of construction workers on actual job sites. Second, owing to limited number of participants, the current study did not conduct statistical analysis for objective measures (i.e., heart rate, skin temperature and skin conductance). Accordingly, researchers are recommended to conduct statistical analysis for these measures. Third, this study explored the interaction of physical and mental stress using a single construction task (i.e., manual material handling with backpack technique). Backpack technique was utilized in this study instead of more common technique of carrying with both hands because the current study intended to collect reliable EDA signals during the experiments and a research which compared different body part concluded that palms are the most sensitive and suitable landmark to collect EDA signals (van Dooren et al. 2012). Accordingly, future studies may explore the interaction of physical and mental stress using the more common manual material handling technique as well as variety of other construction tasks. Fourth, the participants in this study were relatively young (18 to 40 years), while in many countries, the proportion of older workers is increasing rapidly (Quezada et al. 2016; Y.K. et al. 2015). Older workers in comparison to their young counterparts, are more prone to physical stress and fatigue development, attributed to their lower work capacity (Kenny et al. 2008) and decreased muscle mass and strength (Thomas 2010). For that reason, prospective studies should explore the interaction of physical and mental stress for older construction workers. Last but not the least, in the current experimentation, a repeated cognitive task was utilized to induce mental stress. On actual jobsites, there could be several other mental stressors too, including but not limited to other work/task-related, management-related, and interpersonal-related stressors. Accordingly, future studies should explore the effect of these on physical stress of construction workers too.

Conclusions

Given the wide prevalence of physical and mental stress among construction workers, the current study investigated the effect of cognitive task-led mental stress on physical stress development in a controlled environment, using subjective and objective measures. The results found that perception of physical exertion was significantly higher for combined physical and mental stress as compared to physical stress only. Combined physical and mental stress also led to increased skin temperature and skin conductance whereas heart rate remains unaffected. The results along with previous studies for physical exertion modeling suggest that skin temperature may perhaps prove to be a more sensitive and better measure than widely used heart rate, for both conditions; physical stress only and combined physical and cognitive task-led mental stress. The results also indicate inter-individual variability for increase in physical stress because of mental stress which underpins the need for individualized training and interventions as well. Overall, the study has enhanced our understanding related to the interaction of physical and mental stress, which in turn can assist in improving occupational health and safety for construction workers.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1: Statistical results for difference in physical exertion

	F-value	P-value	Partial Eta Squared
Time	57.4	**<0.01**	0.89
Stress	12.67	**<0.01**	0.64
Time x Stress	1.62	0.21	0.19

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Note: ECG refers to electrocardiography; the instrumented vest was worn under the shirt for actual experimentation, here it is worn over the shirt for illustrative purposes only

Fig. 4. Ratings of perceived exertion scores for the two conditions.

Note: * indicates $p < 0.05$; bars indicate standard deviation

Fig. 5. Difference in normalized heart rate for the two stress conditions

Fig. 6. Difference in normalized skin temperature for the two stress conditions

Fig.7. Difference in normalized skin conductance for the two stress conditions

Fig. 8. Physical exertion at the end of experiment