Construction Worker Workload Assessment for Human-Human versus Human-Robot Collaboration in Wood Assembly

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ABSTRACT

Recent advances in robotics and artificial intelligence have influenced the broader adoption of human-robot collaboration (HRC) in industries such as manufacturing and healthcare, but the same cannot be said about construction due to the dynamic nature of the work environment. To facilitate informed decision-making in HRC adoption, there is a need to evaluate the potential benefits of incorporating robots in construction activities. This study evaluates the impact of HRC on construction workers' workload. Experiments involving human-robot collaborative wood assembly tasks were conducted and workload levels of humans in different scenarios were evaluated using physiological data collected with a wearable sensing device. Thereafter, a survey was administered to participants to assess their mental workload. Findings show that HRC posed less workload on workers compared to human-human collaboration, which demonstrates the potential benefits of HRC in the aspect of workload or fatigue reduction among construction workers, and thus could help enhance productivity.

INTRODUCTION

The construction industry falls short in productivity when compared to other sectors like the manufacturing sector (Liu et al. 2021; Abioye et al. 2021). This could be attributed to the slow adoption rate of new technologies in the construction industry as well as the shortage of labor (Liu et al. 2021). Due to the dynamic, hazardous, and stressful nature of construction sites and activities, it is no surprise that workers would shy away from such activities that could lead to musculoskeletal disorders and other work-related sicknesses (Liang et al. 2021). Robots have been viewed in present times as a viable method of augmenting productivity in the construction industry (Abioye et al. 2021; Firth et al. 2022). Human-robot collaboration (HRC) is presently an important process used to facilitate the execution of tasks in extreme environments (Prewett et al. 2010) like outer space, cold regions, and radioactive environments. It provides a complementary environment for more efficient work execution by combining the capabilities of humans and robots in different tasks (Vásconez and Auat Cheein 2022).

Like working with humans, working with robots also imposes a certain level of workload on humans (Prewett et al. 2010). Workload refers to the cost experienced by a worker, given their capacities, while reaching a particular level of performance on a task with specific requirements (Hart and Staveland 1988; Hart 2006). These requirements generally include both physical and mental tasks of which the impacts are dependent on the capacities of the workers carrying out the tasks (DiDomenico and Nussbaum 2008). For optimum performance of workers and to ensure a healthful environment for workers, it is important to measure and understand the workload of workers in order to identify areas of possible improvements (Aktas Potur et al. 2022). To quantify the amount of effort required by a worker in completing a task, physiological monitoring alone does not provide a worker's perception of the physical and mental work associated with a task (DiDomenico and Nussbaum 2008), therefore, augmenting the physiological responses of workers with their subjective perception, provides a more holistic representation of the workload on a worker in terms of physical and mental resources required (Annett 2002).

Workload assessment is necessary to ensure that workers are allocated the most suitable task as wrong task allocation will not only lead to higher error rates but also more workplace injuries (Chen et al., 2017). Therefore, this study aims to assess construction workers' workload in HRC through a combination of physiological monitoring and subjective perception of humans working with a robot. This is expected to provide information on the difference in physical and mental workloads on workers when working with a robot and when working with other humans.

BACKGROUND

The development and advancements in robotics have promulgated the use of robots for mundane tasks as well as some intelligent tasks (Scholtz 2003). HRC has found a lot of applications in different industries like the medical, manufacturing, and transportation industries (Lin et al. 2020; Matheson et al. 2019). The construction industry is not left out in this aspect. Although not yet advanced in the construction industry compared to the earlier listed industries (Zhang et al. 2023), HRC is beginning to gain traction in construction. Construction sites are in most cases unstructured and continually changing as work progresses which makes it difficult for non-intelligent robots to operate. This has resulted in the use of mostly industrial robotic arms placed on moving objects in order to complete a task (Brosque et al. 2020). Despite these limitations, a few intelligent robots have been developed for different activities in the construction industry like bricklaying (James 2020), painting (Asadi et al. 2018), and finishing (Bock 2007) which are all at their early stages of usage. These robots, however, still require human assistance for effective operation in construction environments, especially in activities that require a higher level of rational thinking. This interaction between humans and robots in a shared work environment raises the question of safety as well as the mental and physical workload on the worker for efficient work execution (Liu et al. 2021).

Workload assessment can generally be classified into three categories—physiological, subjective, and performance-based assessment (Yagoda 2010). Physiological assessment monitors the biological impact of a task on a worker, subjective assessment provides information on the perceived level of workload according to the worker, while performance-based assessment measures the actual performance of the worker on the task rather than its impact on the worker (Yagoda 2010). The NASA-TLX is one of the most commonly used scales for measuring the subjective workload of workers in different fields (Chen et al. 2017). It consists of six dimensions that measure various aspects of mental workload which include mental demand, physical demand, temporal demands, performance, effort, and level of frustration (Hart and Staveland 1988). Some studies have relied on its scale for assessing the workload on humans in human-robot collaboration. Novak (2015) estimated the human workload in HRC in a virtual environment using physiological measurements and the NASA-TLX for subjective task performance assessment. The study revealed that task performance showed a better result compared to physiological monitoring. Memar and Esfahami (2019) also assessed human workload in HRC in a simulated environment using brain monitoring and the NASA-TLX for subjective workload monitoring. The result demonstrated an agreement between brain monitoring and subjective workload monitoring. Bustos et al. (2021) found wearable sensors to be a valid tool for physiological monitoring with heart rate as one of the most used parameters in workload assessment.

These studies either considered one of the aspects of workload assessment categories or explored the factors in a virtual environment with activities not directly related to construction activities. The construction environment is mostly unstructured with lots of activities required to be performed in awkward positions and the results from the above studies may not accurately represent a realistic outcome from an actual construction work environment. The present study presents a comparison of the workloads of workers in both HRC and human-human collaboration (HHC) by completing different wood assembly tasks in a real environment.

METHODOLOGY

To achieve the aim of the study, two sets of wood assembly experiments were carried out, one involving HRC and a control experiment of HHC. The experiments consist of nine groups with each group comprising two members—the primary person and the helper. The primary person is responsible for connecting the lumber, while the helper assists with placing and measuring the lumber. The participants in this experiment are college students with basic knowledge of wood assembly tasks. In the HRC experiment, the primary person worked with the robot as the helper while a human helper was used in the HHC experiments. Since subjective workload is generally affected by a number of factors like individual capabilities, age, level of experience, and level of education (Wihardja et al. 2018), helpers used in this experiment were selected based on these factors. All the helpers in this experiment are senior architecture students between the ages of 21 to 29 with about 3 years of work experience. The same primary persons were used for both the HRC and the corresponding HHC. The robot used in this experiment was the four-wheeled Clearpath Husky A200 with Universal Robot 5 e-Series and a 2-finger Robotiq gripper. To assess the workload of the participants, physiological data were collected from the participants as well as their perceived workload by administering a questionnaire at the end of each experiment.

Experiment Task

Two sets of wood assembly tasks were set up for this experiment, one, a 2-dimensional (2D) structure and the other, a 3-dimensional (3D) structure. Of the nine groups of participants, four groups performed the 2D structure experiment while the remaining five performed the 3D structure experiment. The 2D structure is made up of six joints while the 3D structure has extra five joints that connect the 2D structure to another similar 2D structure. These two wood assembly setups were completed using both HHC and HRC for comparison.

Physiological Monitoring

Different metrics have been proposed by different studies for biological monitoring in workload assessment such as heart rate variability, respiratory rate, body temperature, body posture, blink frequency, blood pressure, etc. which are suitable for different activities (Awolusi et al. 2018; Vásconez and Cheein 2022). In this study, heart rate was considered as the metric for physiological monitoring. Heart rate has been extensively used by researchers for the physiological health monitoring of workers (Aryal et al. 2017; Chen and Tserng 2022; Umer et al. 2022). According to a state-of-the-art review by Anwer et al. (2021), the heart pumps more blood to increase blood flow around the body during physical activities for more muscle contraction which leads to increased heartbeat as the heart stroke volume cannot be raised suddenly. Therefore, mean heart rate is a good indicator of stress and workload. Heart rate data were obtained from the primary persons in both the HHC and HRC experiments for comparison with the Fitbit sensor as the wearable device used for the data collection as shown in Figure 1.

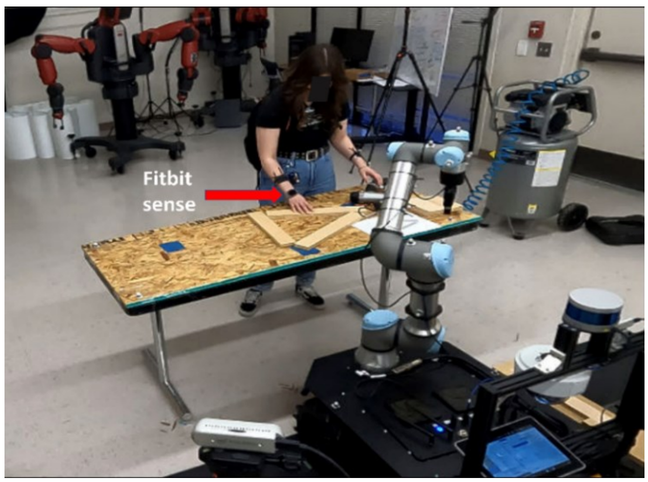

Figure 1. Primary participant working with a robot in HRC setup.

Workload Perception

The NASA-TLX questionnaire, one of the most widely used tools to measure a worker's subjective workload (Potur et al. 2022) was used to evaluate the participant's subjective workload in completing the different tasks. It is a multi-dimensional rating scale used in human workload assessment, comprising six workload-related factors combined to develop a dependable workload approximation (Hart and Staveland 1988; Novak et al. 2015). The six factors consider the perception of the participants on how much physical activity was required to complete the task, the mental activity required, the pace of the tasks, the sense of accomplishment felt, the effort required to complete each task, and the level of frustration and insecurity felt in the process. There are two main parts of the NASA-TLX with the first consisting of raw rating scales for workers to rate the level of perceived demand of each of the six factors, and the second part involving 15 pairwise comparisons of all the factors to determine the number of times each factor comes out more important than the other. The adjusted ratings of the scales are then obtained by multiplying the number of counts from the pairwise comparison with the raw scale rating (Potur et al. 2022). In this study, however, only the raw scale rating of the factors was considered. According to Hart (2006), the raw NASA-TLX is easier to apply and the review of 29 studies that compared both the weighted and raw NASA-TLX showed very little to no difference in the result.

RESULT AND DISCUSSION

To compare the workload on the primary person in both HRC and HHC, their heart rate data and the perceived workload were analyzed to assess the workload on the participants.

Physiological Monitoring Result

The primary person in each group was made to wear the Fitbit sensor on the wrist during the HHC and HRC experiments, and the heart rate data extracted after the experiment. The average heart rate of the primary person (in bpm) throughout the experiment was calculated as shown in Figure 2. Heart rate has been used by different researchers as a physiological metric for measuring the amount of workload on a worker. The result (Figure 2) shows a trend of lower heart rates in HRC when compared with HHC with only group 1 as an exception, with an average reduction of 2.9% for all participants. This suggests a lower workload for the participants in the HRC setup. Only the results from 8 groups were included as the ninth group did not show up for the HRC experiment.

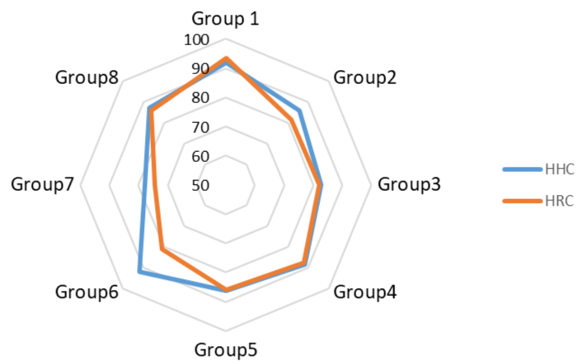

Figure 2. Average heart rate of participants in HHC and HRC.

Workload Perception Result

The Raw NASA-TLX was administered to all the participants (primary persons and helpers) at the end of the experiments to measure the participants perceived workload on six factors. The factors include mental demand (MD), physical demand (PD), temporal demand (TD), Performance (PE), effort (EF), and frustration (FR). Only the results from the primary persons were considered in this study for comparison. Figure 3 shows the mean scale rating of the perceived workload by the primary persons in HHC and HRC experiments. It can be observed that overall, working with a robot posed less workload on the participants compared to working with humans with temporal demand and mental demand having the highest ratings in HHC and HRC respectively.

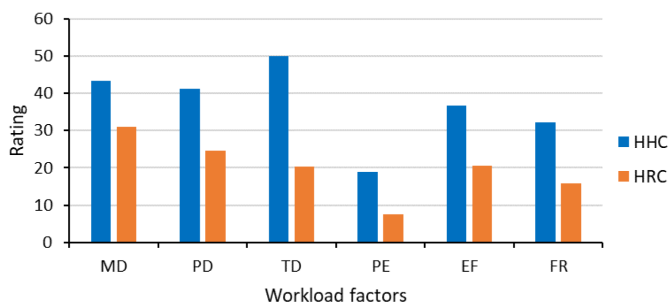

Figure 3. Overall mean ratings of both 2D and 3D experiments

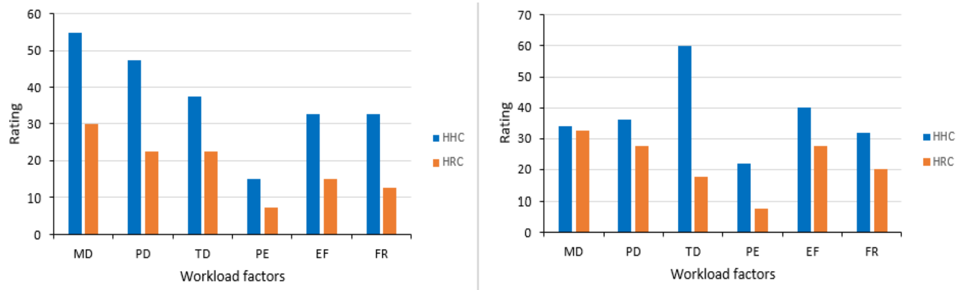

Figure 4. (a) 2D experiment (b) 3D experiment

Mental Demand (MD): Mental demand generally refers to the level of thinking and decision-making required to complete a task (Hart and Staveland 1988). It provides insight into the worker's opinion on the complexity of the task. From Figure 4, in HRC, the participants felt less mental demand on average—28% less compared to HHC. Results of the MD in the two difficulty levels of the experiment (Figures 4a and 4b) indicate that the participants also experienced less MD in both experiments with about 45% less MD in HRC compared to HHC in the 2D experiment.

Physical Demand (PD): This refers to the required physical activity for a task. It consists of all the maneuvering necessary for task completion. Wood assembly is a physically demanding task because of the various sequence of activities it requires (Lee 2017). The result of the experiment showed an overall 39% reduction in physical demand on the primary participants when working with robots compared to working with humans. The lower physical demand in the HRC experiment could be attributed to the primary person focusing only on the lumber connection compared to HHC where the primary person, although assisted by the human helper, had to take part in measuring and marking the lumber. This was done by the robot in the HRC experiment.

Temporal Demand (TD): Temporal demand deals with the pace of the task and the time pressure felt during task execution (Hart 2006). As expected, the HRC experiment showed an overall 59% reduction in temporal demand compared to the HHC with a 70% reduction when only the 3D task is considered as the robot reduces the task on the primary person in the HRC experiment.

Performance (PE), Effort (EF), and Frustration (FR): Performance is the degree of success and satisfaction felt by a worker in achieving the goals of a task, effort refers to the perceived work difficulty by the worker, while frustration refers to the level of insecurity and stress compared to gratification and contentment experienced (Potur et al. 2022; Hart and Staveland 1988). Overall, these three factors saw a reduction in HRC compared to the HHC with a reduction of 60% in performance, 44% in effort, and 50% in frustration.

CONCLUSION

This study presents a workload evaluation of workers in HRC through physiological and subjective workload assessment by comparing the workload of workers in HHC and HRC. Wood assembly tasks were performed by the participants in a controlled environment to simulate an actual construction site activity. The NASA-TLX was used as a tool for subjective assessment of the participants while the physiological workload was evaluated by obtaining data on the heart rate of the participants with a wearable sensing device. The result showed a significant reduction in subjective workloads of the workers with a reduction of 28% in mental demand, 39% in physical demand, 59% in temporal demand, 60% in performance, 44% in effort, and 50% in frustration. The physiological monitoring of the participants also showed a general reduction in workload with a 2.9% decrease in heart rate of the participants in the HRC setup. Although this study was conducted in a controlled real environment, which could affect the result of the experiment when compared to outdoor uncontrolled environment, it provides a more practical result compared to existing studies which are mostly conducted in virtual environments. The findings of this study are expected to provide more scientifically informed decision-making in the adoption of human-robot collaboration in the construction industry.

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