Assessing Workers' Mental Stress in Hand-over Activities during Human-robot Collaboration

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Human-robot collaboration (HRC) is an emerging research area that has gained tremendous attention from both academia and industry. Since some robot-related factors can elicit mental stress or have negative psychological effects on human workers, it is essential to understand these factors and maintain workers' mental stress at a low level. Galvanic Skin Response (GSR) measures skin conductance and is known to be a physiological measurement that reflects short-term mental stress. Typically, skin conductance increases in response to greater mental stress. In this study, the mental stress caused by the hand-over activities of a collaborative robot was investigated using both GSR as an objective measurement and NASA-Task Load Index (TLX) as a subjective assessment. Several robot-related factors that may lead to mental stress were experimentally examined. GSR outcomes indicated that end effector approaching within workers' view, low end effector speed, and constrained end effector trajectory led to a significantly lower skin conductance. Some aspects of the NASA-TLX also indicated that speed and trajectory significantly affected the scores. Yet, no significant differences were found between approaching directions regarding NASA-TLX scores.

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INTRODUCTION

In recent years, the concept of human-robot collaboration (HRC) has been widely adopted in a variety of industries. In HRC, a human operator and a robot share the workplace and work together in a collaborative way. HRC takes advantage of the flexibility of human and the endurance of robots to substantially improve productivity (Villani et al., 2018). A robot adopted in HRC is typically referred to as a collaborative robot or a co-robot. As co-robots are designed to work alongside workers, human workers' safety, including both mental and physical safety, is a top priority in robot design. Previous studies have shown that co-robots have significant psychological effects on workers besides physical collision as human tend to treat their co-robot teammate as a social entity (Sauppé & Mutlu, 2015). A co-robot can be a stressor to evoke mental stress when it appears that it can hurt people. For example, if a co-robot with a sharp end effector moves quickly toward a worker, or a co-robot moves unpredictably, workers could feel fear because the robot appears to harm him or her. Therefore, it is important to understand workers' mental stress during HRC and ensure that co-robots are human-friendly and psychologically acceptable (Kokabe et al., 2008).

A number of methods have been adopted to quantify mental stress including both subjective and objective methods. Self-report is one of the most commonly used subjective methods in psychological evaluation. One can design a questionnaire based on psychological knowledge and then calculate the stress index based on the results of questionnaires. A limitation of subjective methods is that participants may answer the questions the way they think the researchers want them to answer (Paulhus & Reid, 1991). Another issue associated with subjective methods is that the participant's responses depend to some extent on their mood on the day of the experiment (Bethel et al., 2007). As a result, it would be complimentary to conduct objective measurements in addition to subjective measurements. For example, galvanic skin response (GSR) can measure emotional sweat induced by sympathetic nervous system activity by detecting the change in skin conductance. This change in skin conductance is sensitive to mental stress and is gone within a few seconds. Therefore, GSR is more likely to reflect short-term stress induced by a sudden change in the surrounding environment than long-term chronic stress (Affanni et al., 2018).

To date, a variety of studies have been conducted using subjective and objective methods to explore relevant robot-related factors that can yield robot motions with lower mental stress and smoother collaboration between human and co-robots. These factors include approaching directions, speed, and trajectories. Regarding the approaching directions, a previous study (Unhelkar et al., 2014) examined approach angles of 90° or 45° of a mobile delivery robot and found that participants were more comfortable with the 45° approach angle. With regard to speed, a previous study (Arai et al., 2010) investigated several psychophysiological responses to high-speed robot movements. It was concluded that higher skin potential was associated with high-speed robot movements. This result suggests that faster robot motion leads to stronger psychological states, such as fear or surprise. Similar conclusions were also reached by Or (2009) and Kulic and Croft (2007). In terms of robot motion trajectories during picking and delivering an object, most research confirmed that the safety, physical comfort legibility, and predictability of robot motions affect the psychological states of human workers (Dehais et al., 2011; Dragan et al., 2015).

In industrial scenarios, "object handover" is a commonly observed task and can be performed by HRC. In this task, a co-robot picks an object and hands it over to a human worker. Yet, the mental stress of workers during these handover HRC tasks has not been fully investigated. In this study, we aim to evaluate the human workers' mental stress caused by the handover motions of a co-robot in different approaching directions, speeds, and trajectories.

This paper consists of five chapters. In chapter II, the methodology is introduced; in chapter III, the results of mental stress measured by subjective and objective methods during HRC are presented. In chapter IV, the results presented in the previous section are analyzed and discussed. Finally, we presented our conclusions in chapter V.

METHOD

Participants

Eight healthy right-handed adults with an age range from 20-32 years (mean = 27.125, SD = 3.4) participated in this study, including four males and four females. All participants were informed and given a consent form prior to the experiment. None of these participants had any physical injuries or surgical procedures within the last 6 months. The participants were asked to not chat with the experimenters during the entire experiment unless they have questions or concerns related to the experiment. This is because speech content can be a stressor and in turn affect the measured stress level (Bari et al., 2018).

Experiment setup and design

The experiments were conducted using a co-robot (Sawyer, Rethink Robotics) with a single robot arm as illustrated in Figure 1. The HRC task included the following key steps: First, the co-robot picked a beverage bottle from a ramp. Once a bottle was picked, the rest of the bottles were placed on the ramp and slid down so that the robot can take a bottle from the same position each time. Next, the robot end effector approached the participants by turning 90° about the vertical axis of its pedestal and handed the bottle to the participants. Third, the participant took the bottle and sorted it into the corresponding container according to the beverage's flavor (cherry, blueberry, or orange). Meanwhile, the co-robot moved its end effector back to the ramp to pick the next bottle.

Figure 1. A hand-over HRC task adopted in the experiment. The co-robot is delivering a beverage bottle to a participant for further sorting.

Three factors that may affect workers' mental stress during HRC were examined: 1) End effector approaching direction toward the participants, 2) End effector approaching speed towards the participants, and 3) End effector motion trajectory to hand over the bottle.

Particularly, two approaching directions were adopted: from the front of the participants or from the right side of the participants. Due to the job configuration in an industrial environment, co-robot could approach human workers from different directions. As workers' attention mainly focuses on the task, the co-robot and its end effector may not be in their view all the time, which could affect workers' mental stress levels. For end effector movement speed, a speed of 250 mm/s and 1400 mm/s have been set as the lower and upper boundaries in industrial settings, according to a previous study (Koppenborg (2017). In this study, the co-robot end effector movement speed was set to 500 mm/s and 1000 mm/s for low-speed condition and high-speed condition, respectively.

In terms of the end effector trajectory, three trajectories were adopted in this study: expanded trajectory, constrained trajectory and sudden stop trajectory (Figure 2). During the expanded trajectory (Figure 2a), the co-robot end effector directly moves from the bottle storage area to the participant without any retraction. During the constrained trajectory (Figure 2b), the co-robot end effector first retracted back to a location close to the robot pedestal after picking up a bottle and bringing the bottle to the participants. The sudden stop trajectory is similar to the expanded trajectory, but the end effector stops for 2 seconds in the middle of the moving path (marked as point 3 in Figure 2a). Overall, the experiment followed a randomized factorial design. For each combination, a trial includes sorting five beverage bottles consecutively. A 90-second rest was provided between each trial.

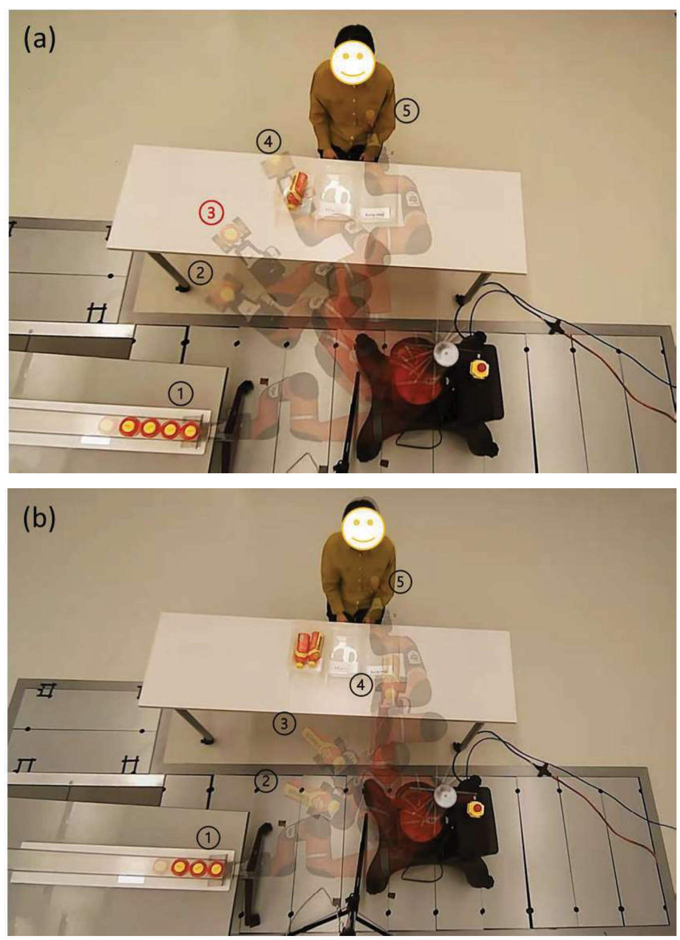

Figure 2. Video frames illustrating trajectories used in the experiment. (a) Expanded trajectory and sudden stop trajectory.

Frame marked by number 3 in red is where the sudden stop occurs during the sudden stop trajectory. (b) Constrained trajectory.

Skin conductance

The skin conductance was measured by a pair of GSR sensors (Shimmer3 GSR+). GSR measures the activity of the sweat glands. Although the sweat glands are located all over the body, it is important that the electrodes are placed in the areas of the skin that contain more sweat glands to acquire a good GSR signal quality. There are two types of sweat glands distributed across our skin: apocrine and eccrine glands. The eccrine glands reflect emotional activity and can be found all over our bodies. GSR electrodes are usually placed on the fingers, feet, or palms because they have a higher density of sweat glands. We choose palms to place the electrodes in this experiment as palms have the highest density of eccrine sweat glands.

A pair of sensors were placed on the lower part of the palm of the non-dominant hand to detect the electrodermal activity. It is common to attach the GSR electrodes on the non-dominant hand because the participant is less likely to move it during the recording. This approach will avoid generating artefacts in the GSR signal because the participant needs to use the dominant hand to hand over the bottle from the end effector of the co-robot. As all of the participants are right-handed, the GSR electrodes were placed on their left hands (Figure 3).

Figure 3. GSR sensor placement diagram

GSR signal is comprised of 1) a low-frequency tonic component, which reflects the subject's general psychophysiological state and its autonomic regulation, and 2) a higher frequency phasic component, which is the superposed higher-frequency change directly related to an external stimulus. A MATLAB application (Ledalab V3.4.9) was used to separate the GSR into tonic and phasic components and extract features following the decomposition of the GSR signal into its tonic and phasic components. There are two methods to quantify each component: Continuous Deconvolution Analysis (CDA) and Discrete deconvolution Analysis (DDA). Although DDA employs a strict nonnegative deconvolution, CDA merely tries to minimize negativity so that the analysis is more robust (Lutin et al., 2021). Therefore, in this study, CDA was adopted. The raw GSR data was recorded at 256 Hz and down-sampled to 64 Hz. The extracted feature is the mean value of the phasic component of the GSR during each condition. Since GSR can be easily affected by individual differences and circumstance temperature, the data were normalized by the maximum mean value of each participant, as shown in Equation 1.

$$\boldsymbol{SR_{i,j}} = \frac{\boldsymbol{R_{i,j}}}{\boldsymbol{R_{i,jmax}}} \quad \text{(Eq. 1)}$$

where $\boldsymbol{i}$ is the number of the participant ($\boldsymbol{i}$ =1, 2, ..., 8) and j is the number of the experiment conditions ($\boldsymbol{j}$ =1, 2, ..., 12). $\boldsymbol{R_{i,j}}$ is the obtained mean value over the repetitions of the $\boldsymbol{i_{th}}$ participant at the $\boldsymbol{j_{th}}$ condition. $\boldsymbol{R_{i,jmax}}$ is the maximum mean value out of $\boldsymbol{i_{th}}$ person, $\boldsymbol{SR_i}$ is the normalized mean skin conductance for the $\boldsymbol{i_{th}}$ person at the $\boldsymbol{j_{th}}$ condition.

Subjective measurements

Self-ratings of mental workload were collected immediately after each trial. The participant will be asked to fill NASA-Task Load Index (TLX) questionnaire, which uses six dimensions to assess subjective workload: mental demand, physical demand, temporal demand, performance, effort, and frustration.

Statistical analysis

Three-way repeated measures ANOVA and post-hoc Tukey HSD test were used to investigate whether approaching direction, end effector speed and end effector trajectory has a significant effect on GSR output and TLX ratings. The significance level was set at 0.05.

RESULTS

Skin conductance

A three-way repeated measures ANOVA indicated statistically significant main effects of approaching direction (F (1,7) = 8.296, p = 0.024) and speed (F (1,7) = 26.623, p = 0.001) on skin conductance (Figure 4). When the end effector approached the participant from the front side, the skin conductance response was 0.511, whereas approaching from the right side evoked a 0.646 skin conductance response. The skin conductance was 0.672 in the high-speed conditions and 0.482 in the low-speed conditions.

Three-way repeated measures ANOVA also indicated that trajectory also had significant effects on skin conductance (F (2,14) = 4.302, p = 0.035). The result of the post-hoc Tukey test indicated that the sudden stop trajectory and the constrained trajectory were significantly different (p = 0.028). The GSR response is 0.649 during sudden stop trajectory and 0.493 during constrained trajectory. There is no significant difference in GSR response between expanded trajectory and the other two trajectories. In addition, all interaction terms are non-significant.

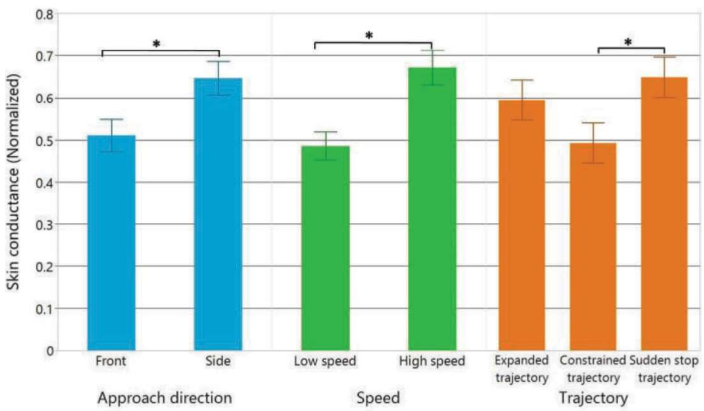

Figure 4. Effects of co-robot approaching direction, speed and trajectory on skin conductance

NASA-TLX scores

For NASA-TLX subjective rating scores, no significant differences were found between approaching direction and NASA-TLX scores. There is a significant main effect of speed on subjective rating of temporal demand ($F(1,7) = 9.248$, $p = 0.019$), performance ($F(1,7) = 21.587$, $p = 0.002$) and frustration ($F(1,7) = 6.265$, $p = 0.041$). There is also a significant main effect of trajectory on subjective rating of frustration ($F(2,14) = 3.885$, $p = 0.045$). The result of the post-hoc Tukey test indicated that the sudden stop trajectory and the constrained trajectory were significantly different ($p = 0.0463$). The mean values of the scores of the six aspects are shown in Figure 5, 6 and 7.

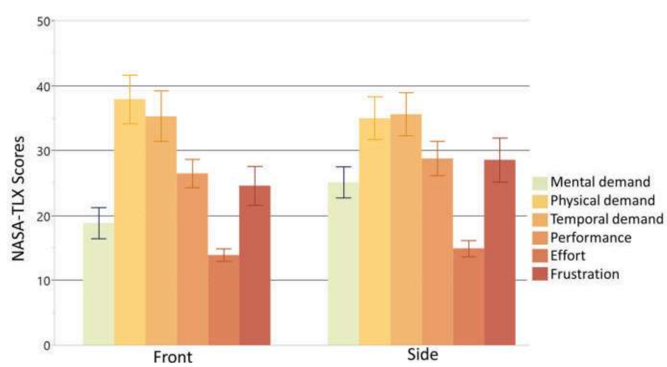

Figure 5. NASA-TLX scores for different approaching directions

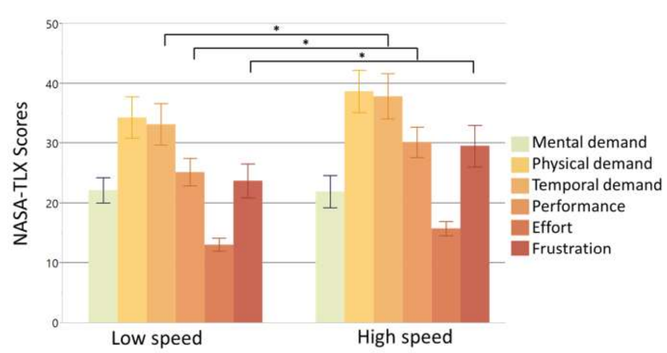

Figure 6. NASA-TLX scores for different end effector speed

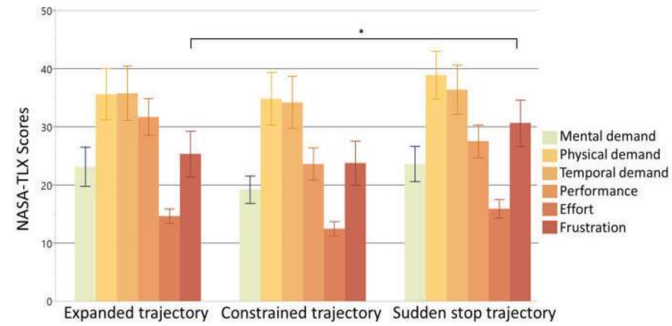

Figure 7. NASA-TLX scores for different end effector trajectories

DISCUSSION

The skin conductance results suggest that the conditions where the end effector approaches the participants from the side cause greater mental stress than the conditions where the end effector approaches from the front. When the end effector moves from one side of the participant, the participants only see part of the robot motion from the peripheral view and have difficulty recognizing the position of the end effector. In contrast, participants have a better vision of the co-robot and its motion when the robot end effector approaches from the front of the participant. This way, participants feel safe and less stressed in handling the HRC tasks.

The results also showed significantly increased skin conductance when participants were under high end effector speed conditions (1000 mm/s). The current study also shows higher scores for temporal demand, performance and frustration at high robot speed. When the co-robot moves toward a worker swiftly, the participant may feel fear because the robot appears to strike him or her. This finding is aligned with a study conducted by Fujita (2010), where a robot manipulator with high moving speed can provoke greater mental stress during a straight approaching.

According to the skin conductance results and "frustration" scores in NASA-TLX, the sudden stop trajectory led to a higher stress level, whereas constrained motion elicited a lower stress level. Considering that the skin conductance is a reliable indicator of arousal (Dawson et al., 2016) and affective reactions (Codispori et al., 2001), the current result indicates that the sudden stop trajectory is associated with frightening and stressful effects as it handed over the bottle in an unpredictable pattern. This is aligned with the findings in Koppenborg et al. (2017) that self-report ratings showed that unpredictable motions result in higher operator mental stress than predictable ones. In our experiment, constrained trajectory is expected to elicit lower mental stress than the expanded trajectory because it might be perceived as a trajectory with less likelihood to strike a worker. Yet, there was no significant difference found between these two conditions.

No statistically significant main effect of approaching direction on NASA-TLX scores. Trajectory also has no significant effects on the five aspects of NASA-TLX scores in addition to "frustration". The reasons for the insignificance could be two-fold: First, the sample size is relatively small as only eight participants took part in this experiment. Additional participants would need to be recruited. Second, the levels of the potential stress-inducing factors adopted in the experiment may be too close to lead to a subjectively distinguishable mental stress difference. Since mental stress in this study is not detected subjectively but physiologically, it is suggested that psychological measurement is necessary to learn the full scope of meatal stress during HRC.

CONCLUSION

As HRC has been flourishing in recent years, there is an urgent need to better understand human workers' mental stress when they are working with their co-robot teammates. In this study, the effects of approaching directions, speed, and trajectories on the mental stress of human workers were investigated with a full-factorial design experiment. The results indicate that low speed, front approaching direction, and a constrained trajectory led to lower skin conductance response and thus lower mental stress. These results suggest that in order to maintain the mental stress of human workers to a low level, the HRC tasks should be designed in a way that 1) the speed of co-robots' end effector should be limited to a level that makes the human worker feel safe and comfortable, 2) the end effector should approach workers within workers' view, and 3) the end effector trajectories should avoid a sudden unpredictable stop.

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