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Effects of arm-support exoskeletons on pointing accuracy and movement

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ABSTRACT

Exoskeletons are wearable devices that support or augment users' physical abilities. Previous studies indicate that they reduce the physical demands of repetitive tasks such as those involving heavy material handling, work performed with arms elevated, and the use of heavy tools. However, there have been concerns about exoskeletons hindering movement and reducing its precision. To this end, the current study investigated how proprioception enables people to point to targets in a blindfolded, repetitive pointing task, and their ability to recalibrate their pointing movement based on visual feedback during an intervening calibration phase, both with and without an arm-support exoskeleton. On each trial, participants were instructed to follow a 40 BPM metronome to point six times alternating between two target points placed either on a vertical or horizontal line. Within a trial, each pointing movement alternated between flexion and extension. Results indicate that participants' average pointing error increased by 4% when they wore an exoskeleton, compared to when they did not. The average pointing error was 12% lower when the target points were aligned vertically as compared to horizontally. It was also observed that the average pointing error was 14% lower during flexion as compared to extension movement. Surprisingly, accuracy did not improve in the post-test as compared to the pre-test phase, likely due to accuracy being high from the beginning. Participants' movement dynamics were analyzed using Recurrence Quantification Analysis. It was found that movements were less deterministic (1% reduction in percentage of determinism) and less stable (13.6% reduction in average diagonal line length on the recurrence plot) when they wore the exoskeleton as compared to when they did not. These results have implications on the design of arm-support exoskeletons and for facilitating their integration into the natural motor synergies in humans.

1. Introduction

1.1. Arm-support exoskeletons

Work-related musculoskeletal disorders (WMSD) involving the neck and shoulders affect a significant number of people around the world and can result in prolonged disability and substantial societal expenses (Bonfiglioli, Caraballo-Arias, & Salmen-Navarro, 2022; Sarquis et al., 2016). Occupations such as construction and manual labor, and assembly line work, involving repetitive and tiring

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movements of the upper limbs, are associated with such risks (Bouffard, Weber, Pearsall, Emery, & Côté, 2020; Liang et al., 2022). Swiftly emerging technology like occupational exoskeletons have gained heightened focus as a potential intervention for managing risks associated with WMSD (Nussbaum, Lowe, de Looze, Harris-Adamson, & Smets, 2019). Exoskeletons can be either active or passive. Active exoskeletons are driven by motors, pneumatic systems, or hydraulic systems, while passive exoskeletons use elastic materials to store and release energy during lifting tasks. The current study explores passive arm-support exoskeletons (ASEs) and reviews prior work investigating the effects of ASEs.

Previous research suggests that ASEs hold promise in alleviating physical strain and fatigue in the neck and shoulder area in repetitive overhead tasks (de Looze, Bosch, Krause, Stadler, & O'sullivan, 2016; Kim, Nussbaum, Smets, & Ranganathan, 2021; Maurice et al., 2019). Additionally, studies suggest that ASEs can reduce the heart rate, discomfort, and perceived exertion associated with such tasks (Maurice et al., 2019; Tyagi, Mukherjee, & Mehta, 2023). As a result, ASEs have the potential to mitigate the risks of WMSD related to the arms and shoulders.

Although the benefits of using exoskeletons in manually demanding occupational tasks are well documented, certain tasks require a high level of precision, such as when bringing the tip of a drill to the head of a screw. Some studies on the use of ASEs have reported reduced quality in performance, with increased precision demands in repetitive overhead tasks, which could be a concern for the widespread adoption of exoskeletons in industrial settings (Alabdulkarim, Kim, & Nussbaum, 2019; Kelson, Kim, Nussbaum, & Srinivasan, 2019). Smets (2019) points out that although many workers suggested using exoskeletons to other workers performing overhead work, some of them expressed concerns about exoskeletons hindering job execution. They stated that wearing ASEs would restrict movement in tight spaces, while sitting, and when bending over. Similarly, Kim et al. (2021) note that restricted joint movements, elevated contact pressure measured by subjective discomfort scores associated with the structural elements of the ASE contacting the skin, and altered working postures could be some issues that arise as industrial workers transition to using exoskeletons.

ASEs work by applying variable levels of torque through the reach envelope of the upper arms. Most devices are spring-based and the amount of torque assistance they provide is a function of the shoulder elevation angle. Recent studies have shown that ASE torques typically range from 3 to 12 Nm and follow bell-shaped profiles, with the peak torque occurring in the range of 90–120 degrees of shoulder elevation, depending on device type and assistance level (de Vries, Murphy, Könemann, Kingma, & de Looze, 2019; Maurice et al., 2019; Watterworth, Dharmaputra, Porto, Cort, & La Delfa, 2023). While such estimates are from static testing of devices, when there is dynamic arm motion the external torque may further depend on the direction of motion (Koopman, Kingma, de Looze, & van Dieën, 2020). Moreover, previous studies have also found a decrease in postural stability when external weights are added on the body, both during quiet stance as well as during repetitive pointing tasks (Cantú, Emery, & Côté, 2014; Qu & Nussbaum, 2009). Hence, in addition to their torque characteristics, it is possible that passive ASEs may also affect pointing accuracy and stability of movements in repetitive pointing tasks owing to their weight (~2–5 kg). These properties contribute significantly to the "context-conditioned variability" that complicates open-loop control of limb movements (Turvey, Fitch, & Tuller, 1982). Hence, it may be non-trivial for a user to correctly anticipate the amount of assistance they receive from ASEs, and control their movements accordingly, especially when movement smoothness and endpoint accuracy are critical. In other words, it would be reasonable to expect that the use of ASE will destabilize the movement smoothness and worsen the end-effector accuracy in repeated pointing tasks, at least until the user's perceptual-motor system calibrates to these effects. In this context, affordance theory may provide useful insights into how ASE use may influence movement control.

1.2. Perceiving affordances

Affordances are properties in the environment that offer opportunities for action, which emerge when an organism with a complimentary property encounters it (Blau & Wagman, 2022; Gibson, 1979; Turvey, 1992). When a worker performs an overhead task in which they must reach and point towards a specific target using a tool (e.g., a drill), they do not perceive the distance to the target in isolation. Instead, they perceive the affordance to reach and point towards the target using the tool, i.e., their action boundary. A study by Carello, Grosofsky, Reichel, Solomon, and Turvey (1989) found that participants judged reachable distances based on the ratio of the target distance to their arm length. During tool use, the body and the tool operate as a unified system, causing a transition of the end-effector from the hand to the tool itself (Gibson, 1979; Mangalam et al., 2022; Maravita & Iriki, 2004; Pagano & Day, 2020; Pagano & Turvey, 1998). For example, when participants made pointing movements between targets using rods of different lengths attached to their index finger, they coordinated their arm joints to stabilize the movement of the tip of the rod, regardless of the length of the rod (Valk, Mouton, & Bongers, 2016). The role of perception is to guide coordinated actions to achieve goals, and hence perception and motor control should be investigated together as part of a dynamic animal-environment system.

Given our dynamic interactions with the environment, and our ability to manipulate the environment and the objects around us to form tools, it is necessary for us to swiftly adapt to changes. The perception-action system exhibits the necessary adaptability to accommodate alterations in our ability in order to establish accuracy after a tool or other modification is introduced (Altenhoff, Pagano, Kil, & Burg, 2017; Brand & de Oliveira, 2017; Day et al., 2019; Pagano & Day, 2020; Venkatakrishnan et al., 2023). For example, Altenhoff et al. (2017) found that the performance of participants with no experience in performing surgery improved as they used a simulated surgical tool for a short span of 10 min. Calibration is the mechanism by which organisms use feedback from the environment and ongoing activity to appropriately scale their actions to achieve their goal (Bingham & Pagano, 1998; Lobo, Heras-Escribano, & Travieso, 2018). It can be distinguished from adaptation, which includes perceptual-motor calibration processes but also purely sensory adaptation such as increased sensitivity during dark adaptation and decreased sensitivity resulting sensory aftereffects. Typically, studies on calibration have underscored the malleability of the human perception-action system in response to perceptual-motor perturbations (Day et al., 2019; Scott & Gray, 2010; Solini, Bhargava, & Pagano, 2021). In a virtual reality task where participants were asked to reach and point towards targets at different distances, Day et al. (2019) found that participants calibrate to altered representations of their hands after receiving feedback while using such representations. In pointing tasks, people receive visual and proprioceptive information about the affordance to reach and point to targets. We can expect that people would use such feedback from their movement and pointing accuracy to calibrate to the changes in affordances brought about by wearing exoskeletons and to scale their actions appropriately.

1.3. Movement direction

Previous studies have reported kinematic differences based on the direction of motion of the arm without any external torque-induced perturbation (Gaveau, Berret, Angelaki, & Papaxanthis, 2016; Gaveau & Papaxanthis, 2011). For example, Gaveau and Papaxanthis (2011) explored vertical arm movements, 45° above and below the shoulder joint and found that hand acceleration profiles were different in the upward and downward directions. Additionally, in the case of horizontal arm motion, Saunier, Paillard, Vargas, and Pozzo (2015) found that the endpoint accuracy was much better when the arm moved towards the body as compared to away from the body. Even with external perturbations, the human perception-action system can adapt to changes, thus demonstrating its stability. Bastide, Vignais, Geffard, and Berret (2018) studied the impact of an ASE on upward and downward movement of the arm. They found that the velocity of movement was lower when participants wore an ASE as compared to when they did not. They also found that the velocity profiles were different in the upward and downward motion regardless of whether they wore the exoskeleton or not. In another study using an ASE, Kelson et al. (2019) instructed participants to engage in an overhead repetitive tapping task, observing that participants exhibited lower precision in the vertical direction compared to the horizontal. Thus, previous literature indicates that movement precision and kinematics are complex in horizontal and vertical directions, both with and without wearing an ASE. Given that ASEs are intended to aid shoulder elevation, one would anticipate consistent support properties in the vertical plane. However, during horizontal movements involving flexion and abduction of the upper arm at the same time, the external torque exerted by the ASE may have a more intricate and potentially inconsistent impact on the movement. Thus, it would be reasonable to expect that when performing a repetitive pointing task, the movement dynamics and accuracy of the end-effector will depend on the direction of motion and whether the arm is moving towards the body or away from it.

1.4. The current study

The current study investigated whether pointing accuracy and end-effector kinematics were affected by the use of an arm-support exoskeleton in a blindfolded, repetitive pointing task, and how exoskeleton use affected the ability to recalibrate pointing movements based on visual feedback during an intervening calibration phase. On each trial, the pointing movements were either in a vertical or horizontal direction, alternating between a flexion or extension of the right arm. A pretest-calibration-posttest design was used in the experiment, and all participants performed the task with and without wearing an ASE. To understand how ASEs affect precision, participants' pointing accuracy was analyzed. The dynamics of the movement of the pointing tool they used for the task were analyzed using a nonlinear analysis technique called Recurrence Quantification Analysis (RQA), which can quantify the periodicity and stability of movements in repetitive tasks.

Based upon the justifications given above, the hypotheses for the current study are as follows:

H1: Pointing error will be larger when participants wear the exoskeleton as compared to when they do not.

H2: Pointing error will reduce in the posttest phase as compared to the pretest phase, regardless of whether participants perform the task wearing the exoskeleton or not.

H3: The magnitude of pointing error will be lower in the vertical direction compared to the horizontal direction.

H4: The magnitude of pointing error will be lower in flexion movement as compared to extension movement.

H5: The movement of the pointing tool will be more deterministic and stable when participants do not wear the exoskeleton as compared to when they do wear it.

H6: The determinism and stability of the movement of the pointing tool will be higher in the vertical direction compared to the horizontal direction.

H7: As trials progress, the movement of the pointing tool will become more deterministic and stable.

2. Methods

2.1. Participants

Considering the experimental design, an a-priori power analysis was performed using G*Power software package (Faul, Erdfelder, Buchner, & Lang, 2009) for a repeated-measures, within-factors ANOVA, using a medium effect size f of 0.25 and an alpha of 0.05. It revealed that a sample size of 16 would produce power >0.8. Seventeen Clemson University students participated in the study for partial course credit after providing informed consent (9 females, age $M = 20.76$, $SD = 4.80$). All participants were right-handed, had normal or corrected to normal visual acuity, and no self-reported musculoskeletal injuries within 12 months prior to participation. The study was performed with approval of the Institutional Review Board of Clemson University.

2.2. Apparatus and material

Ekso Bionics EVO (Fig. 1), a passive arm-support exoskeleton was used in the current study. It weighs 4.3 kg and uses a gas spring-based cam mechanism. It consists of a waist strap and arm straps, the size of which were selected to fit each participant. Interchangeable spring cartridges could be used to change the exoskeleton torque/support strength, and an internal linkage system converted spring compression into shoulder moment. The torque setting could be adjusted to one of three levels – low, medium, or high, but was set to medium throughout the study. Further details about the exoskeleton can be found on the website shared in the description of Fig. 1.

A paper poster (122 cm × 91.5 cm) with target points printed on it was pinned to a wall (Fig. 2a). The targets were white spots at the center of black circles (1 cm radius) numbered from 1 through 8 (Fig. 2b). The targets were arranged in two rows and four columns. The top and bottom row were 30 cm above and below the center of the poster. The alternate columns were separated by 45 cm each, while the first and last column was separated by 56.5 cm. Two whiteboard marker pens were joined to form a cross-shaped pointing tool and was used to point to the targets during the task. The kinematics of every tip of the pointing tool was tracked using passive reflective markers attached using tape. As seen in Fig. 2a, reflective markers were also attached to the poster (above or below each printed target point) to accurately track the position of the pointing tool with respect to the targets. Triaxial coordinates of all the markers were recorded at 120 Hz using a 12-camera motion capture system (Qualisys, Inc., Gothenburg, Sweden).

2.3. Procedure and experimental design

Each participant's shoulder height, shoulder width, total height, weight, and right arm length were measured upon arrival at the laboratory. Following this, the poster was pinned to the wall at a height such that the participant's shoulder aligned to 20 cm above the bottom row of targets. The experimenter then detailed the task to the participant and instructed them to stand at a point marked on the

Fig. 1. Ekso Bionics EVO upper-arm exoskeleton (Retrieved from https://eksobionics.com/ekso-evo/).

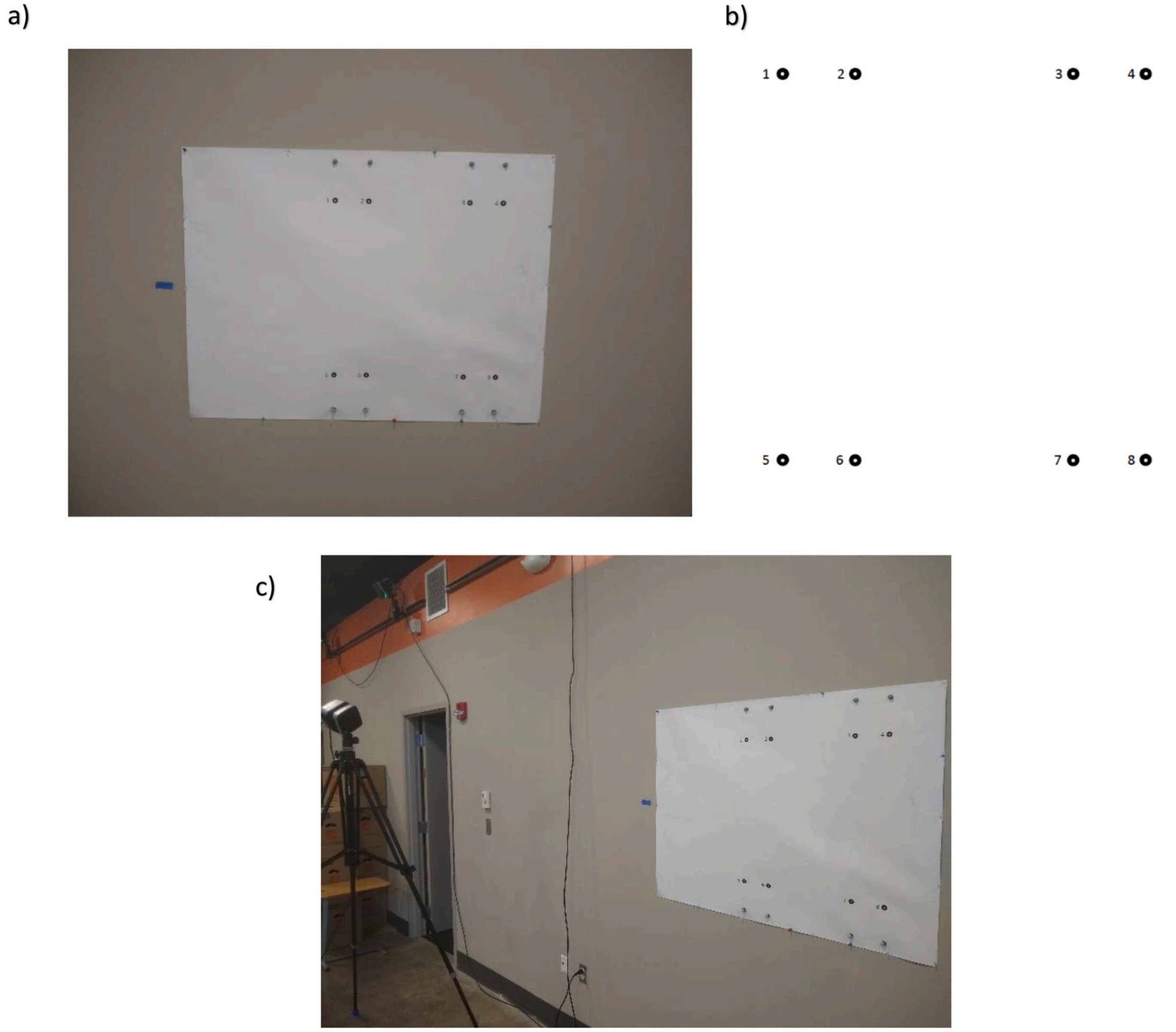

Fig. 2. a) The target poster pinned to the wall; b) Arrangement of target points on the poster; c) The experimental set-up.

ground, that was 80% of their right arm length away from the poster. All participants performed the task without wearing the exoskeleton in the first part of the experiment. This was followed by the second part where they performed the same task wearing the exoskeleton. This order was not randomized because participants did not have any experience using exoskeletons, and we wanted to get a baseline of pointing accuracy for each participant prior to their wearing the exoskeleton. Each part of the experiment was divided into three phases: pretest, calibration, and posttest. After finishing the three phases without wearing the exoskeleton, and following a short break, participants donned the exoskeleton with assistance from the experimenter, the experimenter turned it on, and then the participant familiarized themselves with it before repeating the three phases with the exoskeleton on.

At the beginning of each phase, the experimenter played a 40 beats per minute metronome and confirmed that the participant could hear it clearly. On each trial, the participant was asked to place the pointing tool on one of the eight target points on the poster using their right arm. Then a second target point placed vertically above or below the first target or placed horizontally to the right of the first target, was announced to the participant. Participants were instructed to point six times alternating between the two target points as accurately as possible, following the metronome. Participants were told that the white spots at the center of black circles were the targets. The exact verbal instruction was to "use the pointing tool in a single smooth movement to point back and forth six times between the two target points as accurately as possible, by following the metronome". Prior to the start of the experiment, the experimenter also demonstrated what good performance looked like, by placing the tip of the pointing tool on the white spots/targets. Thus, within each trial, the six pointing movements alternated between flexion and extension. For example, pointing movement from target 2 to 4 was considered as extension, while the movement from 4 to 2 was flexion. Similarly, movement from 2 to 6 was considered as flexion, while 6 to 2 was extension. Throughout the experiment, participants stood such that the midline of their body was in line with the target points 2 and 6. Only targets 2, 4, 6 and 8 were used during pre and posttest phases, while only targets 1, 3, 5 and 7 were used during calibration. After placing the pointing tool on the first target point, participants performed the six pointing movements with their eyes closed during pre and posttest, while they performed the entire task with their eyes open in the calibration phase. Thus, participants did not get any visual feedback about their performance outcome during the pretest and posttest phases, but they received this feedback during the calibration phase.

A within-subjects design was followed in this experiment, with 2 conditions (whether participants wore the exoskeleton or not), 3 phases (pretest, calibration, posttest) and 2 directions of movement (vertical or horizontal) repeated for 4 trials, resulting in a total of 48 trials per participant. Since each trial consisted of 6 flexion/extension movements, participants made 288 pointing movements in total. Participants took about an hour to complete the entire experiment.

2.4. Data preparation

The reflective marker trajectories were labeled using the Qualisys Track Manager (QTM) software (QTM version 2022.1, build 7420, RT protocol versions 1.0–1.23 supported). The trajectory measurements were in units of millimeters. The velocity timeseries

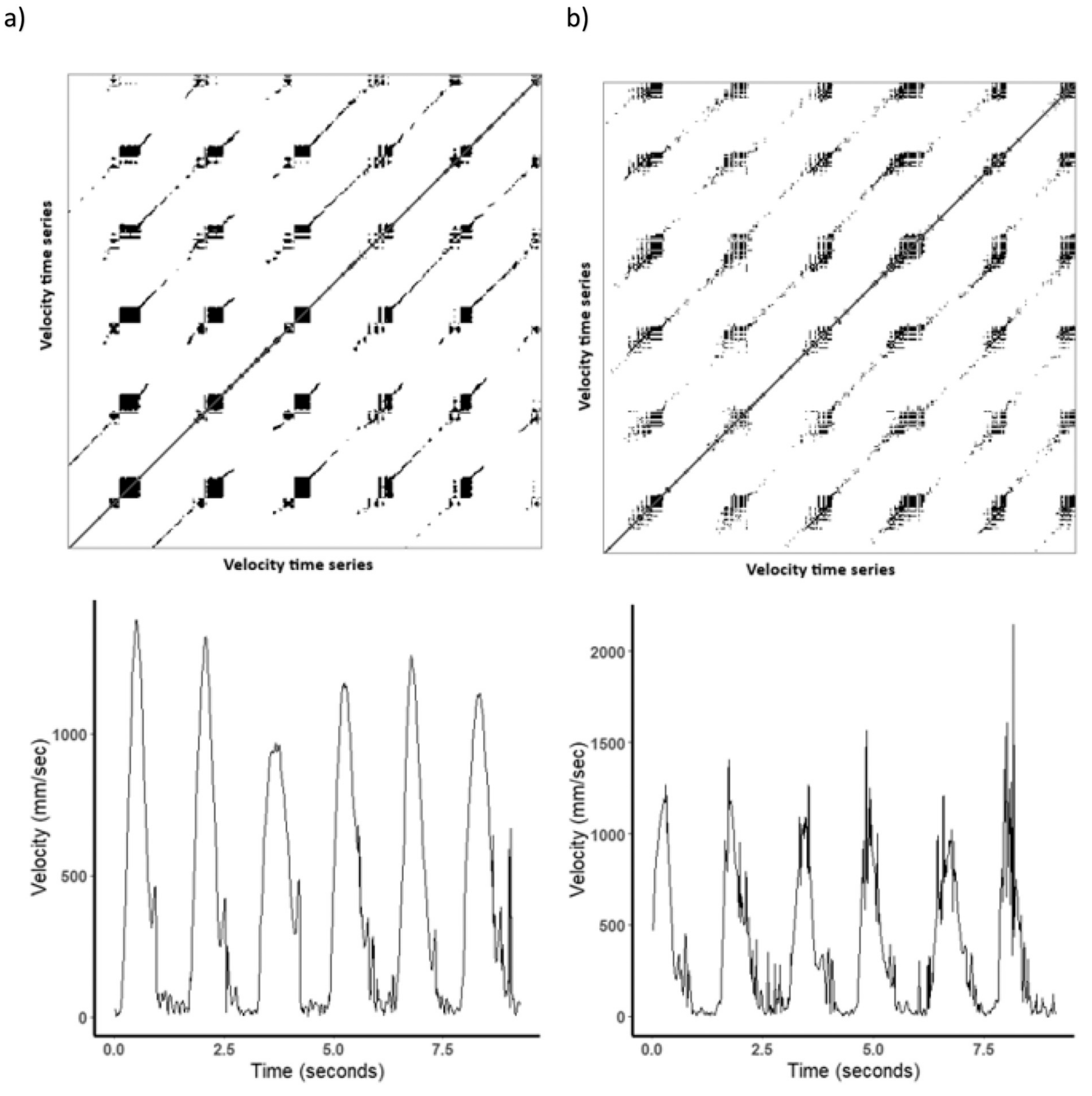

Fig. 3. a) Sample RP (top) and time series (bottom) for a trial where the participant wore the exoskeleton, and the direction of pointing was vertical; b) Sample RP (top) and time series (bottom) for a trial where the participant wore the exoskeleton, and the direction of pointing was horizontal.

data for each trial was divided into six segments corresponding to the six back and forth movements between the target points. For each movement towards a target point, the frame corresponding to the minimum velocity for that movement was identified and the (x, y) position coordinates at these frames were extracted. These frames were also confirmed manually by playing the video of each trial on the QTM software. In the few cases where participants overshot and came back to their intended target location, these final points were identified manually using the QTM software. However, such cases were minimal since the participants were asked to follow the metronome and execute smooth movements to travel between targets. Thus, for each movement in the pre and posttest phase, the coordinates of the tip of the pointing tool that participants placed on the poster, along with the coordinates of the target point for the movement were extracted. The pointing error was computed as the distance between the pointed target location and the actual target location. This pointing error was the dependent variable used in the current study.

For the calibration phase, using QTM, the beginning and end of each trial was manually identified. The velocity of the pointing tip was estimated from the position trajectory of the reflective marker. RQA was performed on the velocity time series for each trial in the calibration phase.

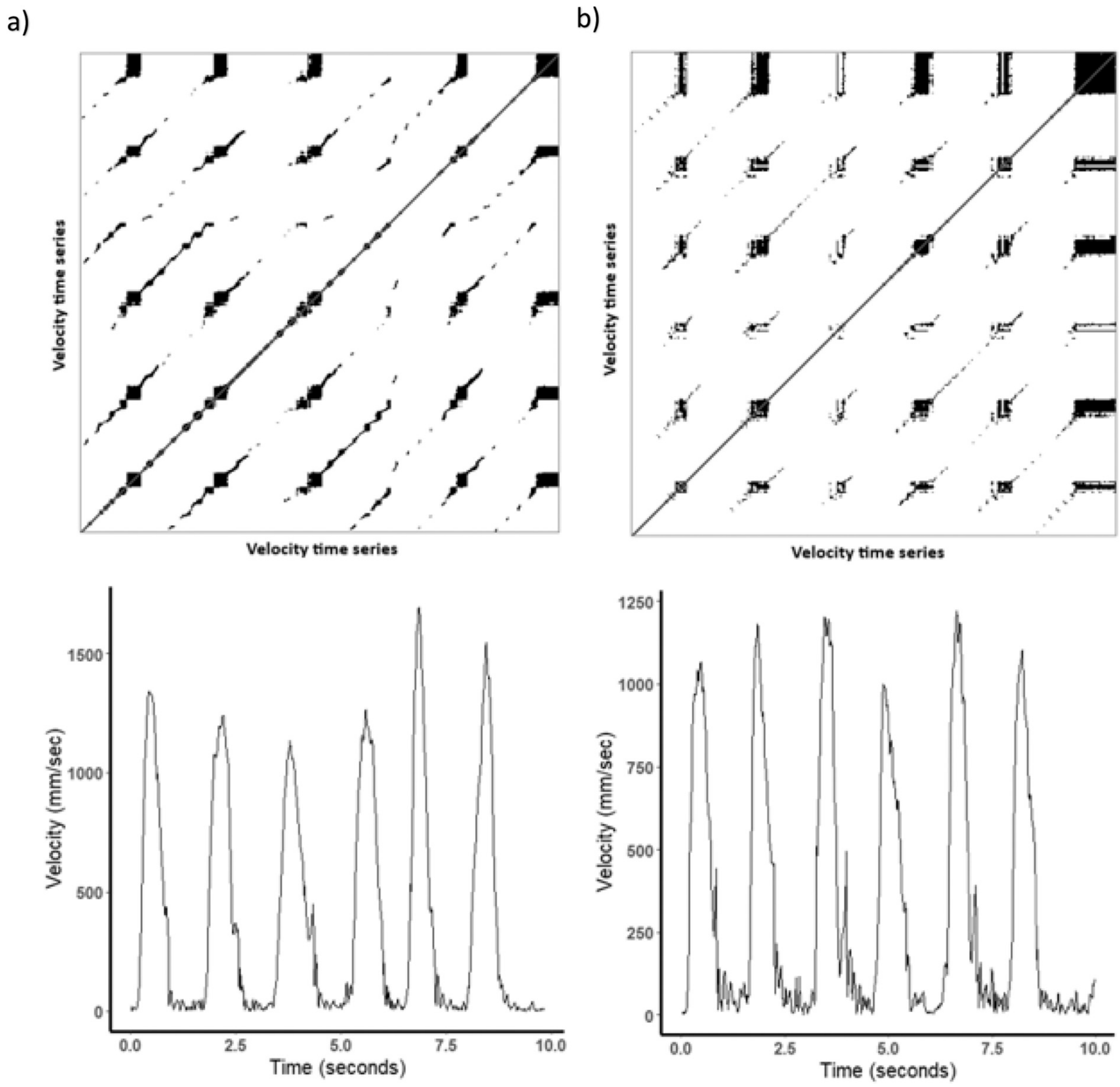

Fig. 4. a) Sample RP (top) and time series (bottom) for a trial where the participant did not wear the exoskeleton, and the direction of pointing was vertical; b) Sample RP (top) and time series (bottom) for a trial where the participant did not wear the exoskeleton and the direction of pointing was horizontal.

2.5. Recurrence quantification analysis (RQA)

RQA is a nonlinear analysis technique used for time series data to quantify recurring patterns that occur at all possible lags of time given the length of the time series (Webber Jr & Marwan, 2014; Webber Jr & Zbilut, 1994, 2005). In fields like behavioral science and movement science, RQA has been successfully used to study differences in postural fluctuations (Balasubramaniam, Riley, & Turvey, 2000; Riley, Balasubramaniam, & Turvey, 1999), exploratory wielding for haptic perception (Riley, Wagman, Santana, Carello, & Turvey, 2002; Wagman, Shockley, Riley, & Turvey, 2001), movement variability in repetitive occupational tasks based on task manipulations (Gaudez & Mouzé-Amady, 2021). In the current study, RQA was used to evaluate the recurring patterns in the velocity of the pointer used for the task, for each trial, for each participant, in the calibration phase (both with and without exoskeleton). The analysis was performed in R statistical software using casnet package (Hasselman, 2022).

To perform RQA, first each velocity time series was rescaled to z-scores. Then a phase space of the rescaled velocity time series was reconstructed using the method of time-delayed embedding (Takens, 1981). To determine an appropriate delay, the Average Mutual Information (AMI) was calculated over increasing time lags. The time lag where the first local minimum (the point where the time series reveal an optimum amount of unique information) appeared was chosen for the phase space reconstruction. The embedding dimension parameter was determined by a first local minimum of False Nearest Neighbors (FNN; cf., Riley et al., 1999). The radius (the area in the phase space where the revisiting trajectories are considered to be recurrent) was allowed to vary within each time series, so that the recurrence rate within the time series was exactly 5% (cf. Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009). These computed lag, dimension and radius were used to optimize the reconstruction for every time series. The recurring patterns in a time series can be represented on a recurrence plot (RP) by charting points where the coordinates of the time series repeat in the phase space (Figs. 3, 4). The following are the relevant measures obtained from the RQA for each trial in this experiment:

1) %DET – The measure that captures the proportion of recurrence points forming diagonal lines on the RP is called the determinism (DET) of the time series. Diagonal structures represent periods in a time series that follow similar paths in their time-evolution when aligned or shifted in time. The more periodic a system is (e.g.: sine waves), in terms of repeating the same paths, the more recurrences will be organized in diagonal lines.
2) Average diagonal line length – The average length of the diagonal lines represents the average time that a system repeats the same path in their time-evolution.
3) MAXLINE – The longest diagonal line on a recurrence plot (MAXLINE) represents the longest uninterrupted period that the system follows the same path, which serves as an indicator of stability of the system: for example, sensitivity to noise and external perturbations creates unstable systems and therefore a shorter longest diagonal line.
4) %LAM – Laminarity captures the stability of the system by quantifying the proportion of recurrence points forming vertical lines on the RP. Vertical structures represent length of periods in a time series in which a state does not change (repeating the same value) or changes very slowly.

2.6. Data analysis

Since a repeated measures design was used in this experiment, variables had considerable nesting. As each participant completed 192 pointing movements (32 trials) in the pretest and posttest phases combined, and 96 pointing movements (16 trials) in the calibration phase, a portion of the variance in their responses can be attributed to a common source – the fact that the same participant was responding multiple times in each condition. Level 1 (within-participant) variables represent those that change from trial to trial. Level 2 (between-participant) variables represent those that change from participant to participant. To properly account for variance between and within participants, Hierarchical Linear Modeling was used (Hofmann, 1997).

Prior to conducting analysis, the extent of nesting in the data was assessed by computing the intraclass correlation coefficient (ICC) from the null model for each dependent variable - pointing error, %DET, Average diagonal line length, LMAX and %LAM. The ICC was calculated to be 0.86 for pointing error, 0.16 for %DET, 0.22 for average diagonal line length, 0.06 for LMAX and 0.11 for %LAM. This indicates that approximately 86% of the variance in pointing error, 16% variance in %DET, 22% variance in average diagonal line length, 6% variance in LMAX and 11% variance in %LAM were associated with the participant and that the assumption of independence was violated in each case. Following a multilevel modeling technique is ideal in this case.

Linear mixed effects models were created to test the effects of the independent variables on each dependent variable. For each analysis, an initial main effects model was run, such that the main effects were included in the analysis all at once. Results for each of these main effects are reported from the initial main effects model. Analysis of two-way interactions was done by adding each interaction term to the main effects model separately. That is, a separate model was run to obtain the results for each two-way interaction term. All models also included a random effect of participant ID. Effect sizes for each fixed effect are presented as the change in R^2 (proportion of variance explained) comparing the model that includes the effect and the same model with the effect removed. The resulting sr^2 (semi-partial r^2) is the percentage of variance uniquely accounted for by the fixed effect (Snijders & Bosker, 2011).

3. Results

3.1. Pointing error

Pointing errors were analyzed for the pretest and posttest phases of the study. A linear mixed effects model was run to assess the effects of condition, phase, direction of movement, type of movement, and pointing number (1 through 6) on pointing error. This model with only the main effects ($AIC = 33{,}724.22$, $df = 8$) offered a significantly better fit to the data than did the null model ($AIC = 33{,}910.23$, $df = 3$), $\Delta\chi^2(5) = 196$, $p < 0.001$. The model explained 87% of the variance in pointing error (conditional $R^2 = 0.866$, marginal $R^2 = 0.008$).

The results indicate a significant effect of condition on pointing error, $F(1, 3242) = 4.70$, $p = 0.03$, $sr^2 = 0.0002$. Pointing error was significantly larger in the exoskeleton condition ($M = 106$, $SE = 25.6$) as compared to the no exoskeleton condition ($M = 102$, $SE = 25.6$). There was also a significant effect of direction of movement on pointing error, $F(1, 3242) = 85.04$, $p < 0.001$, $sr^2 = 0.003$. Pointing error was significantly larger in the horizontal direction ($M = 110.8$, $SE = 25.6$) as compared to the vertical direction ($M = 97.4$, $SE = 25.6$). There was also a significant effect of the type of movement on pointing error, $F(1, 3242) = 104.37$, $p < 0.001$, $sr^2 = 0.004$. Pointing error was significantly larger during extension movement ($M = 111.8$, $SE = 25.6$) as compared to the flexion movement ($M = 96.4$, $SE = 25.6$). There was a significant effect of pointing number as well on pointing error, $F(1, 3242) = 6.35$, $p = 0.01$, $sr^2 = 0.0003$. As the pointing number increased by 1 unit, the pointing error increased by 1.08 units. There was no significant effect of phase on pointing error.

Phase was a significant moderator for the effect of condition, $F(1, 3241) = 5.80$, $p = 0.02$, $sr^2 = 0.0002$ (Fig. 5). When testing simple effects, during pretest phase, pointing error was found to be significantly larger in the exoskeleton condition ($M = 106.60$, $SE = 26.36$) as compared to the no exoskeleton condition ($M = 99.95$, $SE = 26.36$), $t(1614) = -3.25$, $p = 0.001$. However, during the posttest phase, there was no difference in pointing error between the exoskeleton and no exoskeleton conditions.

Movement direction was a significant moderator for the effect of movement type, $F(1, 3241) = 108.04$, $p < 0.001$, $sr^2 = 0.004$ (Fig. 6). When testing simple effects, during horizontal movement, pointing error was found to be significantly larger in the extension movement ($M = 126.17$, $SE = 26.36$) as compared to flexion ($M = 95.39$, $SE = 26.36$), $t(1614) = -13.36$, $p < 0.001$. However, during vertical movement, there was no difference in pointing error between flexion and extension movements.

3.2. RQA variables

The RQA variables were analyzed for the calibration phase of the study. A linear mixed effects model was run to assess the effects of condition, direction of movement, and trial number on %DET. This model with only the main effects ($AIC = -1267.97$, $df = 6$) offered a significantly better fit to the data than did the null model ($AIC = -1220.53$, $df = 3$), $\Delta\chi^2(3) = 53.44$, $p < 0.001$. The model explained 32% of the variance in %DET (conditional $R^2 = 0.32$, marginal $R^2 = 0.15$).

Another linear mixed effects model was run to assess the effects of the same predictor variables on average diagonal line length. This model with only the main effects ($AIC = 1109.72$, $df = 6$) offered a significantly better fit to the data than did the null model ($AIC = 1186.07$, $df = 3$), $\Delta\chi^2(3) = 82.35$, $p < 0.001$. The model explained 44% of the variance in average diagonal line length (conditional

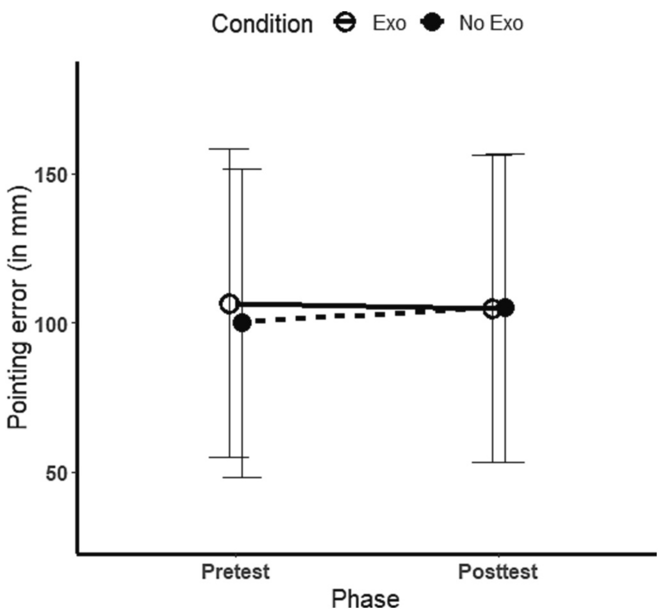

Fig. 5. Interaction between phase and condition. Error bars indicate 95% confidence interval.

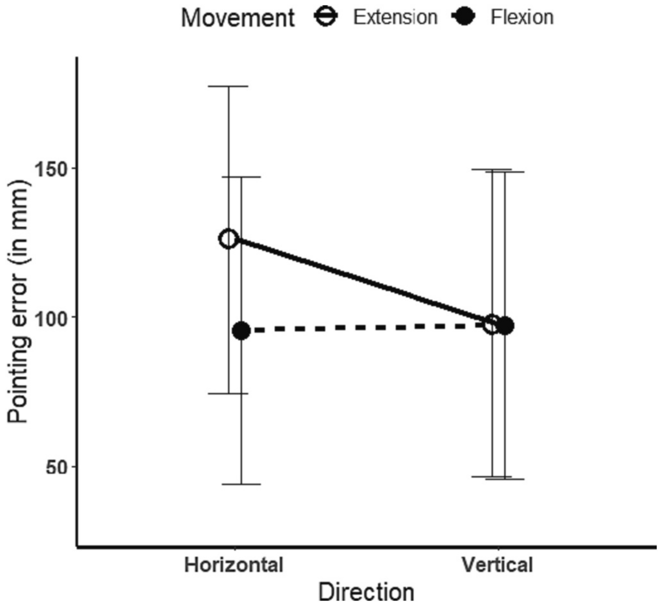

Fig. 6. Interaction between movement direction and movement type. Error bars indicate 95% confidence interval.

$R^2 = 0.44$, marginal $R^2 = 0.20$).

Another linear mixed effects model was run to assess the effects of the predictor variables on LMAX. This model with only the main effects ($AIC = 3753.13$, $df = 6$) offered a significantly better fit to the data than did the null model ($AIC = 3802.48$, $df = 3$), $\Delta\chi^2(3) = 55.35$, $p < 0.001$. The model explained 24% of the variance in average diagonal line length (conditional $R^2 = 0.24$, marginal $R^2 = 0.17$).

Finally, a linear mixed effects model was run to assess the effects of the predictor variables on %LAM. This model with only the main effects ($AIC = -1562.02$, $df = 6$) offered a significantly better fit to the data than did the null model ($AIC = -1533.97$, $df = 3$), $\Delta\chi^2(3) = 34.05$, $p < 0.001$. The model explained 23% of the variance in %LAM (conditional $R^2 = 0.23$, marginal $R^2 = 0.10$).

As expected, condition had a significant effect on %DET, $F(1, 252) = 11.57$, $p < 0.001$, $sr^2 = 0.03$. %DET was significantly higher in the no exoskeleton condition ($M = 0.969$, $SE = 0.003$) as compared to the exoskeleton condition ($M = 0.960$, $SE = 0.003$) (Fig. 7a). Condition also had a significant effect on average diagonal line length, $F(1, 252) = 31.26$, $p < 0.001$, $sr^2 = 0.07$. Average diagonal line length was significantly longer in the no exoskeleton condition ($M = 8.62$, $SE = 0.31$) as compared to the exoskeleton condition ($M = 7.45$, $SE = 0.31$) (Fig. 7b).

Direction of movement had a significant effect on %DET, $F(1, 252) = 46.84$, $p < 0.001$, $sr^2 = 0.12$. %DET was significantly higher in vertical direction ($M = 0.973$, $SE = 0.003$) as compared to the horizontal ($M = 0.955$, $SE = 0.003$). Direction had a significant effect on average diagonal line length as well, $F(1, 252) = 64.44$, $p < 0.001$, $sr^2 = 0.13$. Average diagonal line length was significantly longer in the vertical direction ($M = 8.87$, $SE = 0.31$) as compared to the horizontal condition ($M = 7.20$, $SE = 0.31$). Direction had a significant effect on LMAX as well, $F(1, 252) = 56.96$, $p < 0.001$, $sr^2 = 0.16$. LMAX was significantly longer in the vertical direction ($M = 509$, $SE = 26$) as compared to the horizontal ($M = 295$, $SE = 26$). Direction also had a significant effect on %LAM, $F(1, 252) = 35.8$, $p < 0.001$, $sr^2 = 0.10$. %LAM was significantly higher in vertical direction ($M = 0.975$, $SE = 0.002$) as compared to the horizontal ($M = 0.965$, $SE = 0.002$).

Trial number did not have a significant effect on any of the RQA variables. Condition was a significant moderator for the effect of direction of movement on average diagonal line length, $F(1, 251) = 5.03$, $p = 0.03$, $sr^2 = 0.01$ (Fig. 8). When testing simple effects, for the exoskeleton condition, average diagonal line length was found to be significantly longer in the vertical direction ($M = 8.05$, $SE = 0.35$) as compared to the horizontal direction ($M = 6.85$, $SE = 0.35$), $t(118) = 4.71$, $p < 0.001$. Similarly, for the no exoskeleton condition, average diagonal line length was found to be significantly longer in the vertical direction ($M = 9.69$, $SE = 0.35$) as compared to the horizontal direction ($M = 7.54$, $SE = 0.35$), $t(118) = 7.12$, $p < 0.001$.

4. Discussion

In industrial settings, tasks often involve repetitive execution of movements aimed at locating, reaching, pointing to, or tapping specific targets. These actions are prevalent in assembly line work, manufacturing facilities, and warehouses. Workers engage in rapid movements to manipulate tools, components, and machinery, with precision being paramount to prevent errors and accidents. Exoskeletons are designed to provide support, reduce fatigue, and enhance the overall performance of workers engaged in such tasks. Although previous studies have investigated the effects of ASEs on end-effector precision (Alabdulkarim et al., 2019; Kelson et al., 2019), to our knowledge, accuracy and movement dynamics of the end-effector have not been investigated together in a repetitive

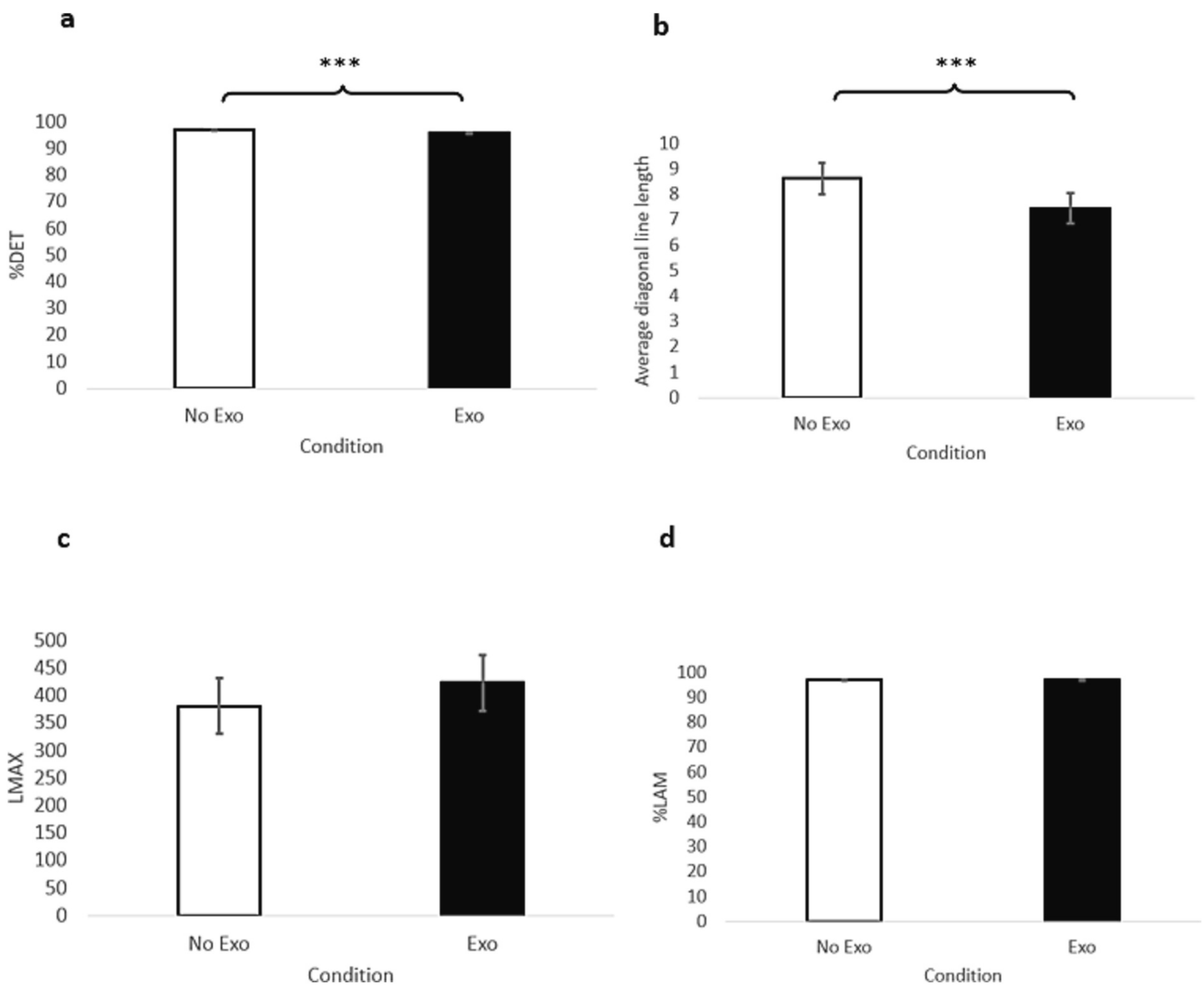

Fig. 7. Effect of exoskeleton vs no exoskeleton condition on a) %DET, b) Average diagonal line length, c) Longest diagonal line length (LMAX), and d) %LMAX. The effect was significant only for %DET and the average diagonal line length. Error bars indicate 95% confidence interval.

pointing task.

Statistical analysis of pointing error revealed that the use of ASE reduced precision in the repetitive pointing task, thereby supporting hypothesis 1. Our results align with studies indicating that the use of external tools, whether a pointing tool or an assistive device like an exoskeleton, influences how we perceive affordances, and thereby, our ability to perform tasks (Blau & Wagman, 2022; Mangalam et al., 2022). However, a small effect size in the current study suggests a low clinical significance of the effect of wearing an exoskeleton on pointing precision. Perhaps this indicates that the participants did not find the task very challenging even as they wore the ASE. It should also be noted that the torque support from the ASE was set to a medium level for the current study, and therefore future studies should test whether a change in torque level could reduce pointing precision.

Using a pretest-calibration-posttest design, the current study investigated whether participants improved their pointing accuracy in the posttest phase as compared to the pretest, by means of the feedback received during calibration phase. Although a different set of target points were used during calibration phase, participants still performed horizontal and vertical movements for the task, and received both visual and proprioceptive feedback since they performed the task with their eyes open. However, the results indicate that there was no significant improvement in the posttest phase compared to the pretest, and therefore did not support hypothesis 2. The interaction between condition and phase also indicates that precision was worse when participants wore the exoskeleton, but only during pretest phase (Fig. 5). Overall, participants tended to have similar accuracy with the exoskeleton as they did without it, which could have been a reason why there was no improvement in the posttest phase.

Since the participants always performed the task first without wearing an ASE, they received feedback about their pointing precision prior to wearing an exoskeleton. Hence, there could have been a learning effect when the tasks were repeated when wearing an exoskeleton (as the order of tasks in our study was not randomized). However, despite this, we observed a small but significant decrease in pointing precision when people wore an ASE in the pre-test condition. That such differences in pre-test results were absent in post-test, validates the importance of the calibration process and the idea that our perception-action system can swiftly adapt to

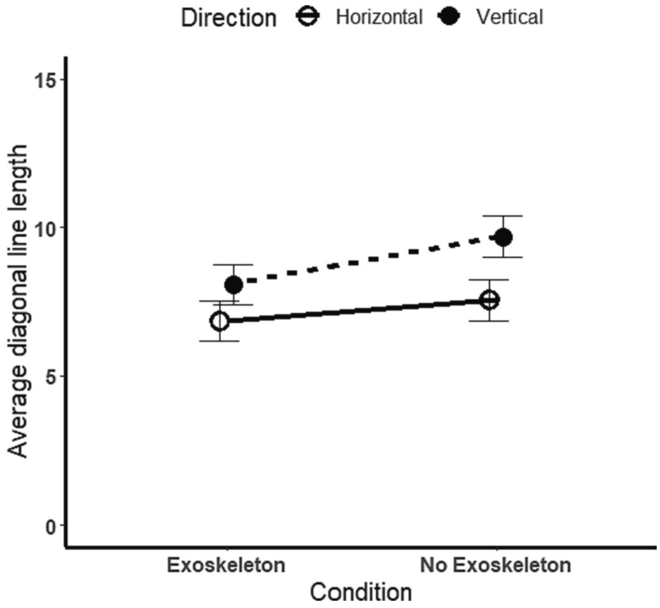

Fig. 8. Interaction between movement direction and exoskeleton condition. Error bars indicate 95% confidence interval.

novel tasks and tools within a short span of time (Altenhoff et al., 2017; Day et al., 2019).

It should be noted that past research has shown lower pointing accuracy, and higher variability, with repetitive pointing that is yoked to an imposed rhythm, as in the present task, compared to when participants are allowed to move freely with preferred motions (Pagano & Turvey, 1995). It is possible that preferred exploratory patterns more effectively reveal perceptual information. Future research should investigate the possibility of diminished kinesthesis during imposed motions and the advantages of preferred motions for both accuracy and the effectiveness of calibration. Such findings would have implications for applications such as assembly line work that can sometimes involve externally imposed rhythmic motions.

Our findings indicate that participants' pointing movements were more accurate in the vertical direction as compared to the horizontal, supporting hypothesis 3. This is inconsistent with the results reported by Kelson et al. (2019), who asked their participants to perform an overhead repetitive tapping task and found that they had lower precision in the vertical direction as compared to the horizontal direction. In the current study, repetitive movements included both shoulder flexion and extension. It was found that participants were more precise during flexion as compared to extension, supporting hypothesis 4. The interaction between movement type and direction indicates that during vertical movements, the pointing error was similar regardless of whether it was flexion or extension (Fig. 6). Only in the horizontal direction, extension movements were more error prone as compared to flexion. However, these results may be explained by the fact that ASEs are generally designed to assist shoulder elevation, which means that their support properties are consistent in the vertical plane. During horizontal movements, when the upper arm is both flexing and abducting at the same time, the external torque provided by the device may have a more complex and rather inconsistent effect on the movement, which may make it difficult for users to anticipate and calibrate to. This may also be partially explained by the relative differences in motor organization/control of horizontal vs. vertical movements (Papaxanthis, Pozzo, & Stapley, 1998).

To successfully perceive affordances and achieve goals, people should control their movements effectively (Blau & Wagman, 2022). Perception and action are therefore mutually informative. In the current study, in addition to the participants' pointing accuracy in the pretest and posttest, the movement dynamics of the pointing tool in the calibration phase was analyzed using RQA to understand whether wearing an ASE restricted participants' movement. As expected, the results indicate that the velocity of the pointing tool was less deterministic when participants wore the ASE. Similarly, the average diagonal line length, which denotes the average time that the same pattern of change in velocity repeats over the six pointing movements in each trial, was shorter when participants wore the ASE. This indicates that the movements were less stable in this case, and perhaps the acceleration and deceleration of the pointing tool was more difficult with the ASE on. Taken together, these results support hypothesis 5.

The direction of movement had a more profound effect on the periodicity and stability of movement. Vertical movements were found to be more deterministic, had a higher laminarity, and longer maximum diagonal lines as compared to horizontal movements, thereby supporting hypothesis 6. Average diagonal line length was also found to be longer in vertical movements, but they were much longer when participants did not wear an ASE as compared to when they did (Fig. 8). This indicates that the ASE had a much larger impact on the stability of vertical movements as compared to horizontal movements. Since ASEs are generally designed to support overhead tasks, and since the torque support kicks in above shoulder level, it is not surprising that it affects the stability of vertical movements more.

Prior studies have indicated that proper feedback allows users to quickly calibrate to hand-held tools and devices like prosthetic limbs (Altenhoff et al., 2017; Brand & de Oliveira, 2017; Day et al., 2019; Pagano & Day, 2020). It seems logical to expect that this phenomenon should generalize to the use of exoskeletons. Specifically, during the calibration phase of the present study, feedback was provided by participants completing the task with their eyes open. Thus, the periodicity and stability of movements were expected to improve over the course of 8 trials. However, our results indicate that this did not happen, and hypothesis 7 was not supported. Movement dynamics did not change as trials progressed in the calibration phase. This might also explain why participants' pointing accuracy did not improve in the posttest as compared to the pretest phase. A study by Balasubramaniam et al. (2000) indicates that when people stand and point towards targets, their postural sway helps them accurately point their tool to the target. That is, the synergy maintained between their posture and the pointing tool plays a role in how they perform the task. Similarly, in the current study, participants might not have learned to maintain this synergy during the calibration phase. Future studies should explore postural sway along with the control of the pointing tool to understand how people achieve this task with an exoskeleton on. Also, since there is a possibility that the number of trials in the calibration phase was not sufficient for participants to improve their performance, future studies should consider increasing the number.

In this study we investigated the effects of wearing an ASE on participants' pointing accuracy, and the movement dynamics of the end-effector in a simple repetitive pointing task. Nonetheless, it is essential to acknowledge several limitations inherent in the current study. One limitation of the study design was that the order of performing the task (first without wearing an ASE and then with an ASE) was not randomized. Due to this, there is a possibility that the decrease in accuracy with the ASE could have been compensated by a learning effect from the no-ASE condition, making our findings conservative. Another limitation is that the current study did not investigate the complexity of muscle activity that could help with accurate, repetitive movements. Future studies should consider using electromyography measures to explore this. It should also be noted that we did not investigate whether there are differences in pointing precision and movement based on sex. It is important to study perception and motor control together since these processes guide and inform each other. Future studies should explore whether higher torque settings on the exoskeleton, and a faster pace of pointing could affect task performance and movement dynamics. On a more theoretical level, future work should be directed towards seeking to better incorporate exoskeletons into the body's tensegrity structure to better facilitate its integration into the body's natural motor synergies (Profeta & Turvey, 2018). As with current research in the areas of tool use, prosthetic limbs, and virtual avatars, the ultimate goal should be to pair effective design with user calibration routines that result in a given exoskeleton becoming part of its user's *embodied action schema*, which represents the body's current action capabilities and which may cause an exoskeleton to "feel as though it is part of the body" (Day et al., 2019; Pagano & Day, 2020).

CRediT authorship contribution statement

Balagopal Raveendranath: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Christopher C. Pagano:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Divya Srinivasan:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors report no conflict of interest.

Data availability

Data will be made available on request.

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