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Effect of fatigue and the absence of visual feedback on shoulder motor control in an healthy population during a reaching task

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ABSTRACT

Introduction: The main role of the upper limb is to position the hand in order to carry out varied activities requiring coordinated multi-joint movement, which requires mobility and stability at the glenohumeral joint. This is made possible by the interaction between active and passive structures as well as the integration of information coming from multiple systems. This interaction can be compromised by factors such as muscle fatigue and lack of visual feedback, leading to decreased performance. Several studies have investigated their isolated effect without looking at their combined effect.

Objective: To measure the specific and the combined effects of shoulder muscles fatigue and of lack of visual feedback on shoulder motor control during a reaching task with the arm in an elevated position.

Methods: 60 healthy participants were randomly assigned to one of four experimental groups: 1) control with visual feedback; 2) control without visual feedback; 3) fatigue with visual feedback; 4) fatigue without visual feedback. Subjects had to perform 10 trials of a reaching task in the KINARM robotic arm. Kinematic variables of interest were time taken to complete the task, final error, initial angle of deviation and area under curve. Non-parametric ANOVAs were used.

Results: Analyses showed that there were statistically significant differences ($p < 0,01$) for the time taken to complete the task (1.15 s compared to 0.70 s), the area under the curve (0.015m^2 compared to 0.009m^2) and the final error (0.025 m compared to 0,011 m) between those who had visual feedback and those who did not. No statistically significant fatigue or feedback X fatigue interaction effects were found for all kinematic variables.

Conclusion: Findings show that lack of visual feedback had an impact on the reaching task performance while fatigue did not. In addition, fatigue did not increase the effect of the lack of visual feedback.

1. Introduction

The main role of the upper limb is to position the hand in space in order to carry out varied activities requiring coordinated multi-joint movement [1–4]. To enable this, the glenohumeral joint has more mobility than any other joint in the body thanks to the absence of bony limitations [1]. However, this great level of mobility implies that the stability of the shoulder is often compromised [5]. Joint stability is provided by the passive (glenohumeral joint capsule, glenohumeral and extracapsular ligaments, glenoid labrum, bony geometry and intra-articular pressure) and active (muscles surrounding the shoulder) structures [5–7]. These structures cannot act alone; they require a dynamic interaction. For example, the passive structures providing physical restraint contribute to stability by supplying the central nervous system

with neural feedback (proprioception) [5]. These signals are then integrated with additional information coming from multiples systems (somatosensory, visual, vestibular) which allows a good control of the active stability components [6].

Proprioceptive information and its integration are therefore essential when selecting motor commands as they are involved in the updating of internal representation of the joint position and movement [6,8,9]. Due to its complexity, shoulder control can potentially be affected by internal or external factors that can alter proprioception [10–13].

One such frequently encountered perturbation influencing shoulder control is muscle fatigue. It is defined as a decreased force-generating capacity or an inability to maintain movement performance [14]. When fatigue, muscle strength, rate of force development power and the

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shortening velocity are reduced [14] and motor unit recruitment [15–19], muscle coordination [20–23], joint kinematics [24,25] and accuracy [14] may all be altered. Movement variability may also increase, leading to kinematic reorganization [26–29]. Some studies have demonstrated the impact of shoulder muscle fatigue on movement control through kinematic (reduced glenohumeral flexion and scapular rotation) and muscular adaptations (early activation of upper trapezius among other muscular recruitment changes) [30–33]. However, a recent study highlighted that, although changes occurred following muscle fatigue, performance (endurance, accuracy and speed) in repetitive reaching task are not diminished [34].

In addition to muscle fatigue, lack of visual feedback also represents one of the main perturbations modulating shoulder control. It is the most important element for the planning of target attainment in the peripersonal space [35]. This is especially true when the movement is done in a new environment as vision is predominantly used to guide the trajectory of the hand [36,37]. Memory-guided reaching has been shown to be less accurate and slower compared to visually-guided reaching [9,38]. In the absence of visual feedback, integration of proprioceptive information from the whole upper limb is highly necessary, especially for the coordination of the adjacent joints [37].

Although, the effect of fatigue [20,23] and lack of visual feedback [38,39] during reaching has been covered in the literature, their combined effect has never been studied. It is of great interest as people are frequently confronted to both fatigue and lack of visual feedback at work or during sport activities. Evaluating their combined effect might help better understand the development of compensatory movements when confronted to both. Given that several sports and manual tasks are performed with the arms in elevated positions and that shoulder control is more challenging in these positions [40], looking at their combined effect in elevated arm position during challenging reaching tasks may highlight some interesting findings. Memory-guided reaching should lead to larger deficits in shoulder control when a disruptive factor such as fatigue is present, as it seems to affect the integration of limb proprioceptive information [14,41,42].

The main objective of this study was to measure the specific and combined effects of shoulder muscles fatigue and lack of visual feedback on shoulder kinematics during a reaching task with the arm in an elevated position. Based on the current literature, we expected the lack of visual feedback would mainly lead to changes in accuracy of the movement and time taken to complete the task [38]. We also hypothesized that changes following fatigue in the group without visual feedback would be greater since movement control during new tasks relies more heavily on visual feedback [9].

2. Methods

2.1. Participants

The population studied was selected using the following admissibility criteria: 1) healthy and right-handed men and women; 2) aged between 18 and 40 years old; 3) absence of upper limb pain or disorder. They were recruited within *Université Laval* and through social media. Recruitment period started in October of 2017 and ended in April of 2018. The sectorial rehabilitation and social integration research ethics committee of the CIUSSS-CN approved this study (#2016-527).

2.2. Study design

Participants took part in one evaluation session. They first filled the Edinburgh Handedness Inventory (EHI) to characterize their upper limb laterality and a form with sociodemographic information and information about their use of the upper limb during work and/or sports. Thereafter, participants were randomly assigned to one of the four experimental groups: 1) control with visual feedback; 2) control without visual feedback; 3) fatigue with visual feedback; 4) fatigue

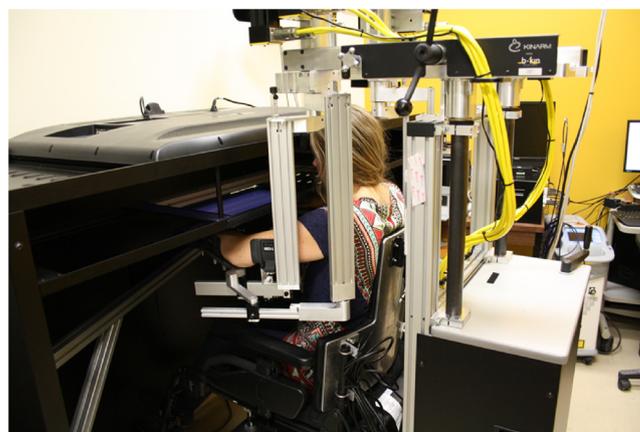


Fig. 1. KINARM setup.

without visual feedback. Randomization was done using a website (sealedenvelope.com) and a bloc randomization (8) was used. Each participant only performed one experimental condition rather than the four to reduce the potential influence of a learning effect had they executed the reaching task four times [9].

Thereafter, patients in the two fatigue groups completed a fatigue protocol immediately followed by the completion of the 10 trials of the reaching task in the KINARM robotic arm (BKIN, Technologies Ltd., Kingston, Ontario, Canada), while the subjects in the two other groups directly completed the reaching task (Fig. 1). The KINARM is a robotized exoskeleton that allows movement of the shoulder (horizontal abduction and adduction) and elbow (flexion and extension) joints to move the hand towards targets in the horizontal plane represented on a two-dimensional virtual reality display [9]. This display system projected targets on a screen placed over the subject's upper limb. The task, which the participants did not practice beforehand, consisted of a series of 5 targets on the virtual screen that the participants had to reach with their right index finger as precisely and rapidly as possible while seated. Targets had a radius of 1 cm and their location was normalised for each participant using arm length so that each one of them had to make movements requiring the same shoulder and elbow range of motion (Fig. 2). Targets appeared on the screen once the previous one had been reached. There was no rest time between each target and each trial, and subject arm was maintained at 90° of elevation (in a plane of movement that was dictated by target position) during the task.

While performing the task, participants encountered a small resistance from the KINARM (6–8 N/m), which increased proportionally to the speed of their movement and was applied perpendicularly to their intended direction, while moving their arm along the virtual screen. The resistance was included to increase the realism of the task since the KINARM removes the resistance normally felt during a movement. Kinematic values were recorded for each trial.

2.3. Fatigue

Participants in the fatigue groups performed a validated experimental upper limb fatigue protocol. [43] While standing, subjects had to perform 3 activities requiring shoulder elevation to induce shoulder fatigue: 1) manipulate screws on a wooden board during 2 min while maintaining the arm at 45° of elevation; 2) raise and lower their right arm against a resistance in the scapular plane (20 repetitions at a resistance corresponding to 20% of the maximum voluntary contraction); 3) raise and lower their right arm against a resistance in the diagonal plane (20 repetitions at a resistance corresponding to 20% of the maximum voluntary contraction). Participants had to repeat this sequence until they reached 10 on the Borg Rating of Perceived Exertion Scale (Borg CR10 Scale) [43].

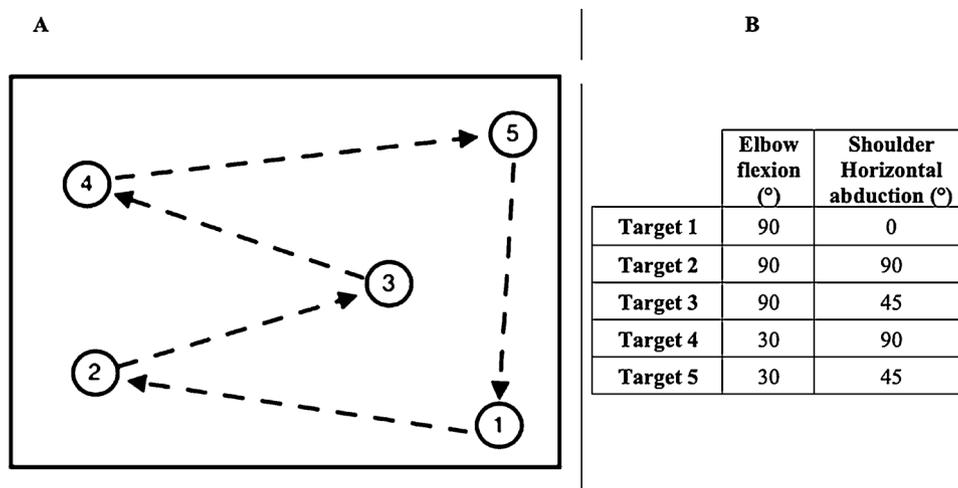


Fig. 2. Additional informations regarding the reaching task: A) Target position on the virtual screen; B) elbow and shoulder joint angles for each target where 0° of horizontal abduction corresponds to the arm in the abduction plane and 90° of horizontal abduction corresponds to the arm in the flexion plane.

2.4. Visual feedback

Participants either had a virtual marker (white dot of 1 cm diameter displayed continuously during the hand movement) of their index finger position shown on the screen while performing the task (visual feedback groups) or they had no feedback other than the targets on the screen, which changed colors from red to green once reached (no visual feedback groups). The subjects in the no feedback groups had therefore to rely almost exclusively on their upper limb proprioception to complete the reaching task.

2.5. Outcome measures

The outcome measures for this study were the upper limb kinematic data. Elbow and shoulder joint angular positions were obtained with the KINARM motor encoders and sampled at 1KHz. Index finger position was calculated by the KINARM software: Dexterit-E (version 3.5.3). Variables of interest, as shown in Fig. 3, included the time taken by the participants to go from one target to another, final error (fERR) which reflected the accuracy of the movement (arc distance between the actual and expected arrival points), the initial angle of endpoint deviation (iANG) which reflected movement planning as it was based on the initial trajectory of the hand (this angle was calculated using the shortest line between two targets and the line corresponding to the initial peak of acceleration) and the area under the curve to show the difference between the actual and the most direct path of the index finger.

2.6. Statistical analyses

Baseline demographic data were compared between-group using non-parametric Mann-Whitney test and chi-square.

For all outcomes, mean values by target and by group were calculated and non-parametric ANOVAs (Package nparLD 2.1, R-software, v.3.3.3), where the effect of fatigue, feedback, and target, as well as the interactions between these factors were analysed. Non-parametric ANOVAs were used since the distributions changed across conditions and that it was not possible to assume that the covariance matrix was a compound-symmetry matrix.

3. Results

60 participants (15 participants/group) were included and randomly assigned to one of the four experimental groups (Table 1 for Participants' characteristics). There were no significant differences

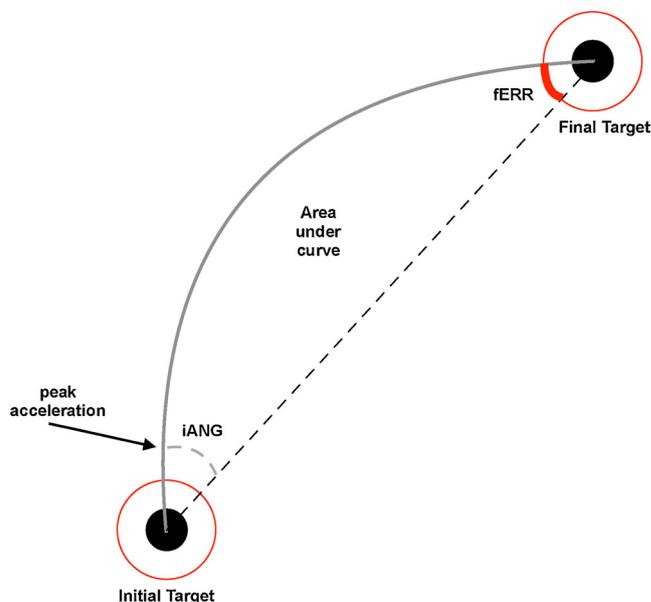


Fig. 3. Horizontal view of selected kinematic variables. This figure depicts the kinematic variables extracted from index finger trajectories. The fERR is measured as the distance between the index and the target when the index crossed the invisible 2-cm radius circle centered on the starting position. The iANG is computed as the angle between: 1) a line joining the position of the index at movement onset and the target; and 2) another line joining the position of the index at movement onset and at its first peak of acceleration.

between the different groups in baseline characteristics. Complete results are presented in Tables 2A and 2B.

3.1. Kinematic data analysis

Analyses showed that those who did not have visual feedback took significantly more time to complete the task (Fatigue effect: $p < 0.01$; 1.15 s for the no visual feedback groups compared to 0.70 s for the visual feedback group). They also displayed a significantly less direct trajectories as there were statistically significant differences for the area under the curve (0.015m^2 compared to 0.009m^2) and the final error (0.025 m compared to 0.011 m). Significant Feedback x Target interaction effect ($p < 0.01$) were also observed for time to complete the task and area under curve variables meaning that the effect of feedback was different across target, which is logical since the level of difficulty

Table 1
Subjects characteristics.

| | Group A | Group B | Group C | Group D |
|--|-------------|-------------|-------------|-------------|
| N | 15 | 15 | 15 | 15 |
| Gender | 6M 9F | 7M 8F | 7M 8F | 7M 8F |
| Age (years) | 23.9 ± 2.7 | 23.5 ± 1.7 | 23.6 ± 1.5 | 23.9 ± 1.7 |
| Height (m) | 1.72 ± 0.09 | 1.71 ± 0.10 | 1.74 ± 0.7 | 1.74 ± 0.11 |
| Weight (kg) | 69.5 ± 17.4 | 72.1 ± 15.3 | 69.4 ± 12.2 | 68.0 ± 12.5 |
| Dominant side | 15R | 15R | 15R | 15R |
| Laterality quotient | 83.3 ± 15.0 | 86.7 ± 18.0 | 82.7 ± 16.2 | 80.0 ± 15.1 |
| Number of participants that reported playing a sport that requires the use of the right upper limb | 13 | 13 | 14 | 15 |
| Patient self-reported usage intensity of their right upper-limb during their sport (%) | 78.1 ± 16.7 | 67.2 ± 25.0 | 78.9 ± 17.2 | 67.3 ± 27.0 |
| Number of participants that reported having a work that requires the use of the right upper limb | 14 | 10 | 12 | 14 |
| Patient self-reported usage intensity of their right upper-limb during their work (%) | 59.6 ± 24.5 | 59.5 ± 23.9 | 38.8 ± 24.5 | 57.9 ± 25.2 |
| Time taken to complete fatigue protocol (s) | | | 582 ± 181 | 582 ± 136 |

Group A: Control without visual feedback.

Group B: Control with visual feedback.

Group C: Fatigue without visual feedback.

Group D: Fatigue with visual feedback.

Table 2A
Table of results (means and SD).

| | | No fatigue + No feedback | No fatigue + Feedback | Fatigue + No feedback | Fatigue + Feedback |
|--|------------|--------------------------|-----------------------|-----------------------|--------------------|
| Area under the curve (m ²) | Target 1-2 | 0.033 ± 0.014 | 0.024 ± 0.010 | 0.034 ± 0.017 | 0.033 ± 0.017 |
| | Target 2-3 | 0.014 ± 0.009 | 0.006 ± 0.003 | 0.009 ± 0.007 | 0.006 ± 0.002 |
| | Target 3-4 | 0.006 ± 0.005 | 0.002 ± 0.001 | 0.011 ± 0.014 | 0.002 ± 0.001 |
| | Target 4-5 | 0.016 ± 0.008 | 0.006 ± 0.002 | 0.012 ± 0.006 | 0.007 ± 0.003 |
| | Target 1-2 | 0.020 ± 0.007 | 0.011 ± 0.006 | 0.023 ± 0.012 | 0.012 ± 0.007 |
| Final error (m) | Target 2-3 | 0.031 ± 0.012 | 0.012 ± 0.006 | 0.022 ± 0.013 | 0.012 ± 0.005 |
| | Target 3-4 | 0.026 ± 0.010 | 0.011 ± 0.003 | 0.025 ± 0.014 | 0.012 ± 0.002 |
| | Target 4-5 | 0.024 ± 0.015 | 0.008 ± 0.003 | 0.019 ± 0.010 | 0.010 ± 0.005 |
| | Target 1-2 | 18.79 ± 7.44 | 15.08 ± 4.59 | 19.60 ± 7.63 | 18.44 ± 8.8 |
| | Target 2-3 | 27.01 ± 11.32 | 22.70 ± 8.03 | 26.12 ± 14.56 | 22.36 ± 5.87 |
| Initial angle of deviation (°) | Target 3-4 | 21.60 ± 7.34 | 20.30 ± 5.93 | 17.80 ± 6.58 | 22.47 ± 10.21 |
| | Target 4-5 | 19.02 ± 6.80 | 13.59 ± 5.30 | 17.81 ± 8.44 | 14.36 ± 6.28 |
| | Target 1-2 | 1.230 ± 0.0374 | 1.043 ± 0.265 | 1.720 ± 0.957 | 1.083 ± 0.215 |
| | Target 2-3 | 0.994 ± 0.589 | 0.600 ± 0.138 | 0.935 ± 0.391 | 0.607 ± 0.095 |
| | Target 3-4 | 0.917 ± 0.569 | 0.522 ± 0.128 | 1.461 ± 1.327 | 0.529 ± 0.106 |
| Time (s) | Target 4-5 | 1.087 ± 0.511 | 0.799 ± 0.181 | 1,219 ± 0.596 | 0.777 ± 0.129 |

Table 2B
Table of results (F value and ETA²).

| Fatigue | | Visual Feedback | | | | Visual Feedback | |
|--|------------|-----------------|------------------|--|------------|-----------------|------------------|
| | | F-value | ETA ² | | | F-value | ETA ² |
| Area under the curve (m ²) | Target 1-2 | 1.307 | 0.220 | Area under the curve (m ²) | Target 1-2 | 1.935 | 0.032 |
| | Target 2-3 | 2.013 | 0.161 | | Target 2-3 | 11.276 | 0.163 |
| | Target 3-4 | 1.847 | 0.310 | | Target 3-4 | 10.741 | 0.156 |
| | Target 4-5 | 0.723 | 0.120 | | Target 4-5 | 22.719 | 0.281 |
| | Target 1-2 | 0.611 | 0.100 | | Target 1-2 | 19.905 | 0.256 |
| Final error (m) | Target 2-3 | 1.803 | 0.185 | Final error (m) | Target 2-3 | 31.814 | 0.354 |
| | Target 3-4 | 0.390 | 0.001 | | Target 3-4 | 41.258 | 0.416 |
| | Target 4-5 | 0.169 | 0.003 | | Target 4-5 | 28.919 | 0.333 |
| | Target 1-2 | 1.288 | 0.220 | | Target 1-2 | 1.760 | 0.029 |
| | Target 2-3 | 0.510 | 0.010 | | Target 2-3 | 2.308 | 0.380 |
| Initial angle of deviation (°) | Target 3-4 | 0.164 | 0.030 | Initial angle of deviation (°) | Target 3-4 | 0.717 | 0.012 |
| | Target 4-5 | 0.140 | 0.002 | | Target 4-5 | 6.572 | 0.102 |
| | Target 1-2 | 0.740 | 0.047 | | Target 1-2 | 11.749 | 0.198 |
| | Target 2-3 | 0.630 | 0.803 | | Target 2-3 | 15.249 | 0.208 |
| | Target 3-4 | 1.770 | 0.030 | | Target 3-4 | 12.036 | 0.172 |
| Time (s) | Target 4-5 | 0.230 | 0.004 | Time (s) | Target 4-5 | 12.229 | 0.174 |

for the trajectory between the targets was not the same for all of them. No Fatigue or Fatigue x Feedback interaction effects were observed (Fig. 4).

A high level of fatigue (mean pre = 7.8/10 on the Borg CR10 Scale) was reached in all of the participants following the fatigue protocol. This level of fatigue gradually dropped during the reaching task (mean 5th repetition = 5.7/10; and mean 10th repetition = 4.4/10 on the Borg

CR10 Scale).

4. Discussion

This study aimed to measure the combined effects of shoulder muscle fatigue and lack of visual feedback on shoulder motor control and to characterize changes in motor patterns during a reaching task

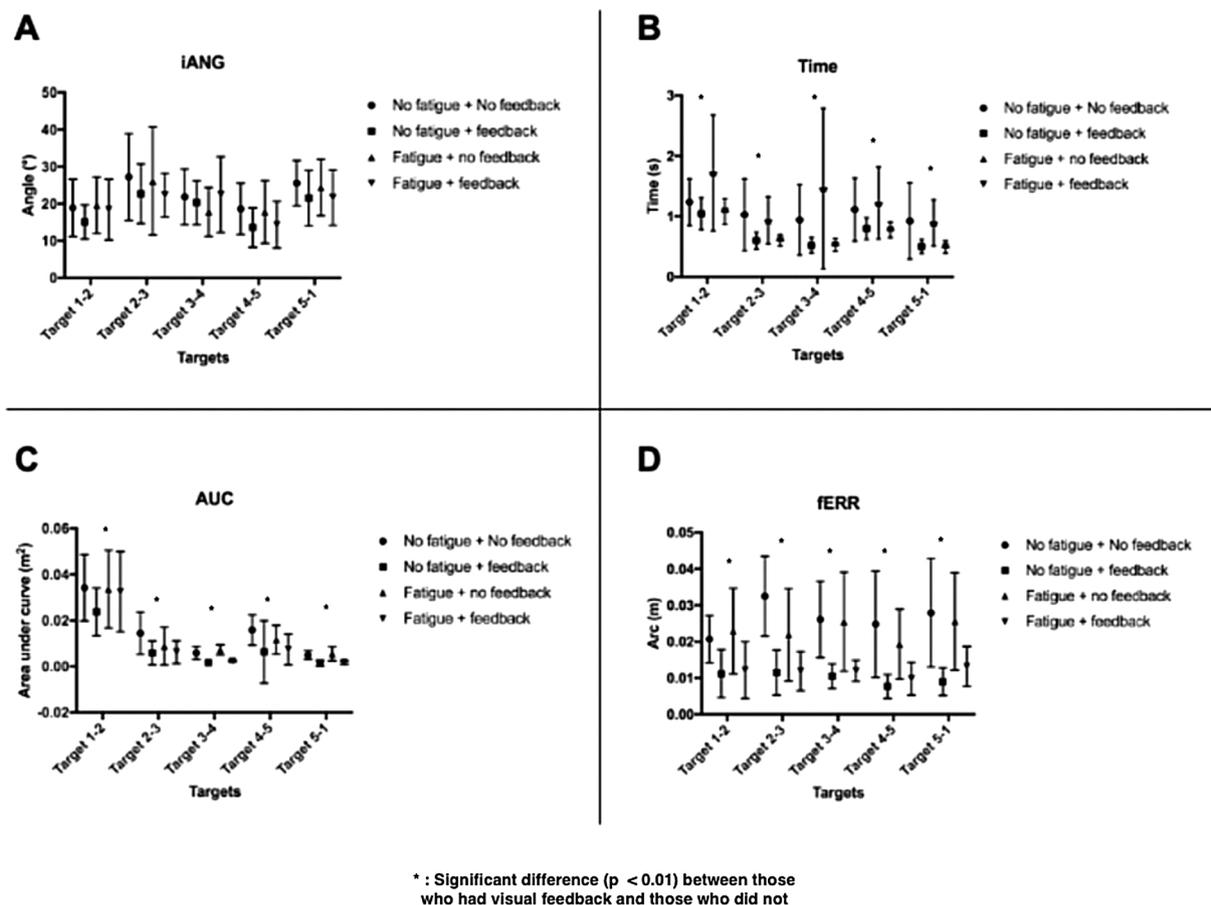


Fig. 4. Kinematic variables for each group and for each trajectory from one target to another. For each group, dots represent mean score of trials 1 through 10. Error bars represent standard deviations. (A) Initial angle of deviation (iANG); (B) Time taken to complete the task; (C) Area under the curve (AUC); (D) Final error (fERR).

with the arm in an elevated position (90° of elevation). We hypothesized that lack of visual feedback would mainly lead to changes in the accuracy of the movement and time taken to complete the task was confirmed by our findings. Our hypothesis that changes following fatigue in the group without visual feedback would be greater was not supported, as there was no fatigue X feedback interaction.

4.1. Effect of fatigue on kinematics

Muscle fatigue has been shown to decrease reaction time [44] as well as muscle response time, although in uni-articular tasks [45]. Those changes could be explained, respectively, by an increased activity in the prefrontal areas of the brain [46] and a decrease in muscle fiber conduction velocity [45]. However, time taken to complete the task was not significantly affected by the fatigue condition in the present study. This could be explained by the fact that there exist infinite ways to complete a multi-joint task which makes it difficult to bring out a consistent pattern.

Furthermore, other studies, which also assessed the effect of fatigue on upper limb kinematics, showed that different motor strategies can be used to compensate for the fatigued joint making it hard to outline a specific kinematic change across the groups [26,27,47,48]. This is consistent with our results and might explain why no significant changes were observed for the fatigue conditions. Also, studies have highlighted an increased variability as a sign of fatigue, especially in a healthy population group, which might further explain the lack of differences between those who had fatigue and those who did not [26–28,33]. A recent study concluded that upper limb fatigue leads to complex kinematic reorganization involving the whole body; especially in the proximal and distal joints of the fatigued one [29]. This

reorganization could be a factor contributing to the greater variability in movements put forward in other studies.

4.2. Effect of visual feedback on kinematics

One study evaluating the impact of visual feedback on reaching movement found a significant difference in accuracy between those who did and did not have visual feedback [9]. This showed that, even within steady conditions, the suppression of visual feedback could lead to changes in movement accuracy [9]. Another study highlighted differences in time and accuracy between those who did and did not have visual feedback while completing a reaching task [49]. These results correlate with our findings and are consistent with current literature [50–53]. They can be explained by the fact that resolution of the visual system is probably greater than proprioception alone to guide movements in new environment. Regarding proprioception, another recent study stated that there are increased spatial and temporal variations in older adults as well as increased movement duration but with maintenance of endpoint accuracy [54]. However, other studies found no differences in accuracy in the absence of visual feedback [39,55–58]; showing that proprioception information alone may compensate for lack of real-time visual input. This goes against the results highlighted in this study, as there was a statistically significant decrease in accuracy variables for those who did not have visual feedback versus those who did. This contrast in the literature might further reinforce the notion that vision and proprioception are not two pieces that need to be added together. They can each play a sufficient, although different, role to allow regulation of final position in reaching movements.

4.3. Effect of combined fatigue and lack of visual feedback on kinematics

As stated earlier, this present study failed to highlight a statistically significant effect on kinematics by the combination of fatigue and lack of visual feedback. In the absence of literature on this subject, we had hypothesized that the combination of both would lead to greater changes related to the lack of visual feedback. We based this on our knowledge that without real-time visual input to execute the reaching task, subjects would rely even more on upper limb proprioceptive information to complete it as accurately as possible. However, their upper limb proprioception would be affected by muscular fatigue, as it has been shown in multiple studies [41,42,59,60], making it harder for them to maintain the same level of accuracy.

These results could have been the product of a task that was too easy for the subjects in terms of its muscular requirements or the lack of sufficient fatigue as subjects recovered from the experimental fatigue protocol during the reaching task.

4.4. Limitations

There are some limitations to this study. First, even though the participants had not practiced the reaching task beforehand, there was a learning effect throughout the experimentation and their 10th trial was often more accurate and quicker than the first one, which could have led to less differences between the different groups. There was also great variability in the motor strategies employed between each subject for the same task and even between each trial for the same subject. This variability could have made it difficult for us to bring out clear differences between each of the groups. Furthermore, since the experimental fatigue was phasic and the reaching task was not too demanding, the fatigue level of the subjects assigned to this group diminished during the execution of the reaching task in the KINARM. A high number of participants (55) also reported playing a sport that requires the use of the right upper limb, making a faster recovery from their state of fatigue possible. Finally, the subjects performed the task in a 2-dimensional plane, but it would have been interesting to do so in a 3-dimensional environment in order to accurately reproduce the demands of daily life tasks.

5. Conclusion

In conclusion, the results of this study show that lack of visual feedback had an impact on the reaching task performance while fatigue did not. Furthermore, findings of our study provide new and additional data to help understand the impact of the combination of muscle fatigue and lack of visual feedback. In this project, the addition of fatigue did not increase the effect of the lack of visual feedback on task performance.

Further studies using more demanding tasks, as a way of measuring the effect of fatigue and the lack of visual feedback on shoulder muscles recruitment patterns, should be initiated in order to improve our knowledge on this matter. Also, it would be interesting to measure the EMG activity of shoulder muscles of to establish if there are differences in their pattern of activation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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