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Evaluation of physical fatigue based on motion analysis in manual handling of loads

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Abstract

Muscle fatigue refers to the transient decrease in the capacity to perform physical actions and can cause productivity loss, human errors, unsafe actions, injuries and work-related musculoskeletal disorders (WMSDs). A total of 13 participants repetitively lifted a 2.5 kg load at a total elevation of 0.5 m, until voluntary exhaustion or intensive pain. Several indicators of muscle fatigue were found, including increased forward bending, micro-expressions, changing load support strategy, holding load closer to the chest during elevation and increase in eccentric movement speed. Volunteers that practiced sports regularly lasted longer in the experiment and it was found that smoking and sedentarism limited the exercise capacity of some subjects. Volunteers increased the wrists and elbows velocity during the experiment. It was verified that half of the volunteers had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others, translating into more impulsive movements. It was concluded that to compensate muscle fatigue, people adapt their working strategy, changing movement patterns, recruiting different muscles and changing kinetic or kinematic components of the movement (like joint angles and velocities).

1. INTRODUCTION

According to Enoka et al. (2008), muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce. It can be categorized as one of the symptoms of blood occlusion, because limited blood flow delivers insufficient oxygen and nutrients, alongside the inadequate removal of metabolic waste products, causing lactate concentrations to rise (Oyewole, 2014).

Manual handling of loads consist of any of the following activities: lifting, holding, putting down, pushing, pulling, carrying or moving of a load. Fatigue accumulation can be extended by practicing proper work/rest time ratio and controlling the lifting variables (Halim et al., 2014).

A significant level of muscle fatigue can cause productivity loss, human errors, unsafe actions, injuries and work-related musculoskeletal disorders (WMSDs) (Sluiter et al., 2003; Toole, 2005; Huang and Hinze, 2006; Hallowell, 2010).

During repetitive and fatiguing work, the musculoskeletal system adapts and uses momentary muscle substitution patterns, which result in more variable and less coordinated movements (Mehta et al., 2015).

A recent review, performed by Srinivasan and Mathiassen (2012) concluded that motor variability is a relevant issue in an occupational context and that there is a great need for studies of motor variability. They suggest future research in creating methods to assess motor variability and study the relationship with occupational tasks and outcomes like fatigue and performance.

The main goals of this study were:

a) Identification of muscle fatigue indicators that could be listed and checked in a real work environment;

b) Definition of a muscle fatigue assessment method based on motion analysis, in order to objectify a measurement technique susceptible of being applied in a real work environment.

2. MATERIAL AND METHODS

2.1. Participant selection

This methodology is a new approach that allows the assessment of common symptoms and behaviors that people demonstrate when starting to feel muscle fatigue

Participants must be healthy, because any diseases or injuries may influence muscle performance and lead to inconsistent findings. Variables like lifestyle, eating habits and medical history are important.

Smoking and alcohol consumption also influence the results, alongside age and gender differences (Al-Mulla et al., 2011). According to Wüst et al. (2008) smokers have lower skeletal muscle fatigue resistance and the increased fatigability is due to the reduction in oxygen supply to the muscle. It was concluded by Bogdanis (2012) that sedentary lifestyle and/or cardiovascular and pulmonary diseases may limit exercise capacity and increase fatigability.

In order to analyze these variables, a questionnaire divided into 4 topics (personal data, lifestyle, eating habits and medical history) was created.

The experiments were conducted in the morning between 8 a.m. and 12 p.m., in order to have rested volunteers. Otherwise, muscle condition would be influenced by daily activities.

2.2. Sample characteristics

A total of 13 participants were recruited, namely, 4 men and 9 women and it was a convenience sample gathered in the university where the study was performed. The analyzed sample of 13 people is not the ideal sample size to generalize the results and future work should include a larger and representative sample.

All volunteers were university students and had normal weight, except one of the males that had more muscular volume than the others, which led to a higher Body Mass Index value (BMI) for that individual. Their characteristics are presented in Table 1. All participants provided informed written consent.

Table 1. Subjects Characteristics

	Age	Height (m)	Weight (kg)	BMI (kg/m^2)
Males	24 ± 0.8	1.83 ± 0.08	76.8 ± 7.3	22.9 ± 2.2
Females	24 ± 1.2	1.65 ± 0.05	62.7 ± 3.8	23.0 ± 1.6

2.3. Apparatus/Equipment

The software used consisted of a motion analysis software available from Video4Coach, namely SkillCapture version 2.0.6 and SkillSpector Version 1.2.4. The first one was used to record the experiment, alongside two Logitech C920 HD Pro Webcams, each one placed in the left and right side of the person, at around 45 degrees. The recordings were then studied in SkillSpector.

A digitizing model and a calibration model were created. The digitizing model included a total of 12 points, namely two on the fingers, two on the wrists, two on the elbows, two on the shoulders, one on the neck and one on the top of the head. Segments were defined as an element going from one point to another. For example, the forearm was the segment between the wrist and elbow points. The calibration model included 8 points, each in every corner of the 50 cm edge cubic structure.

Volunteers had markers placed in strategic parts of the upper body, as shown in Figure 1, in order to improve the video analysis and creation of the body segments in the 3D model, as presented in Figure 2.

The 3D model was built by marking each reference point placed on the volunteer body in each frame (1 frame = 0.03 s) of the video. Since two cameras were used, this had to be done twice, one for each recorded video. Because of this limitation, only the differences between the first and last movements of lifting and lowering were studied, considering that the last movement before voluntary exhaustion is the most representative of muscle fatigue.

The body position was calculated using a DLT algorithm (Direct Linear Transformation) which was found based on the calibration object. This is the mathematical methods used to transform image data into real-world coordinates.

Figure 1. Body Segments and markers

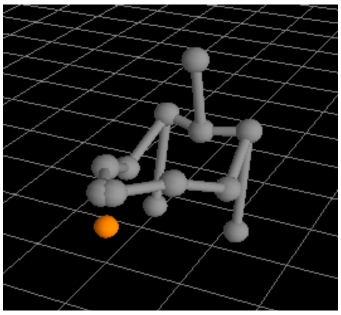

Figure 2. 3D model created in SkillSpector

2.4. Experimental procedure

The study started with the completion of a short questionnaire that covered 4 topics, namely: personal data, lifestyle, eating habits and medical history. After completing the questionnaire and verifying that subjects were eligible for the study, the experiment was explained to the volunteers and informed consent was signed.

The experiment was conducted inside a climatic chamber, where specific conditions were set, namely 25 ± 2 ºC temperature and 49 ± 5 % relative humidity.

At the beginning of the study, a cubic calibration structure with 50 cm edge was placed where the volunteers would perform the exercise, as shown in Figure 3, with the 3 adopted axis that was used. This axis orientation was selected because the program calibration tutorial adopted this orientation.

The volunteers repetitively lifted a 2.5 kg load (dumbbell disk) from a 0.72 m height to 1.22 m, meaning a total elevation of 0.5 m, until voluntary exhaustion or intensive pain, that is, until they no longer could perform the task. While performing the exercise, two video cameras recorded the movements performed and these images were subsequently analyzed. A metronome (100 bpm) marked the pace that volunteers needed to perform the lifting and lowering movements of the load so that all volunteers performed the task under equal conditions. Figure 4 shows the experiment layout and Figure 5 represents the lifting and lowering movement executed by the participants.

Ratings of perceived exertion (RPE) were gathered using the modified Borg scale. Subjects rated their level of fatigue on a scale from 0 (none at all) to 10 (maximal exertion) at the end of the experiment. Subjects were also asked about the physical symptoms they experienced throughout the experiment and these were noted down.

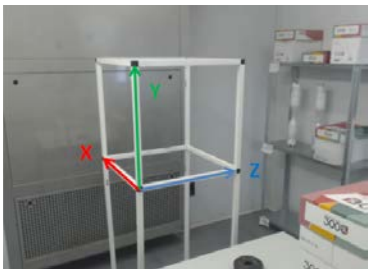

Figure 3. Calibration Object

Figure 4. Experiment layout

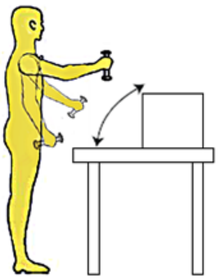

Figure 5. Lifting and lowering movement

2.5. Statistical Analysis

Normality tests were performed in order to determine the normality of the data, namely Shapiro-Wilk, Anderson-Darling, Lillefors, and Jarque-Bera tests. Outliers were detected with Grubbs test.

Student's paired t-test compared the means of two series of measurements performed on the same statistical units, namely the information of the first and final movements.

Box-and-whisker plots were used to present the results.

Tests were carried out to verify the normality assumptions based on skewness and kurtosis, considering the criteria proposed by George and Mallery (2010) of skewness and kurtosis values within ± 2.

3. Results and Discussion

3.1. Questionnaire Results

The questionnaire covered 4 topics, namely: personal data, lifestyle, eating habits and medical history. Table 2 sums the main results of the questionnaire.

In terms of lifestyle, 9 in 13 participants played sports regularly (3 out of 4 males and 6 out of 9 females). On average, both males and females practiced sports 3 times a week. The main activity was training at the gymnasium.

Only 1 female smoked and 4 in 13 (2 out of 4 males and 2 out of 9 females) admitted they had a sedentary lifestyle. In average, males sleep 8 ± 0 h/day while females sleep 7.2 ± 0.4 h/day.

Table 2. Questionnaire results

Name	Plays Sports	Smokes	Sedentary Lifestyle	Coffee Regularly
Male 1	**Yes**	No	No	**Yes**
Male 2	**Yes**	No	**Yes**	**Yes**
Male 3	No	No	**Yes**	**Yes**
Male 4	**Yes**	No	No	**Yes**
Female 1	No	**Yes**	**Yes**	**Yes**
Female 2	No	No	**Yes**	No
Female 3	**Yes**	No	No	**Yes**
Female 4	**Yes**	No	No	No
Female 5	No	No	No	**Yes**
Female 6	**Yes**	No	No	**Yes**
Female 7	**Yes**	No	No	No
Female 8	**Yes**	No	No	**Yes**
Female 9	**Yes**	No	No	**Yes**

A total of 10 people drink coffee regularly (only 3 females don't drink). None of the participants consume alcoholic drinks regularly or was taking a diet or was vegetarian.

Analyzing the data, there is a slight tendency for people that practice sports to hold on longer in the experiment. Female 1 and 2 only kept doing the experiment for 7 and 10 minutes (see Figure 6) and both of them did not practice sports regularly. In the males, male 3 was the only one that didn't practice it regularly but hold for 45 minutes (more 11 minutes than male 2).

The only smoker (10 cigarettes/day) was female 1, the one that only did the experiment for 7 minutes, which shows that smoking may harm physical condition. In terms of sedentarism, female 1 and 2 are the only females that admit they have a sedentary life, showing that the lack of exercise might have an influence on the results. The asthmatic condition of female 2 probably contributed to such a low time.

The asthmatic condition of female 2, probably contributed to such a low time. On males, the results are not conclusive, since male 2 and 3 considered themselves sedentary and hold more than male 1. On the other side, male 4, the person that stayed in the experiment for 1 h, didn't consider to have a sedentary life.

Most volunteers consumed coffee regularly, only female 2, 4 and 7 didn't. Since they consume it regularly, their body already adapted to a certain daily dose and side effects don't appear. Alterations appear when they consume a higher quantity or don't drink it. According to (Poole et al., 2017), coffee consumption was more often associated with benefit than harm for a range of health outcomes. The largest relative risk reduction was obtained at intakes of three to four cups a day versus none. Caffeine can also strengthen their ability to recover from fatigue. In this study, the observed average consumption was 2 coffees/day.

Female 1 combined the negative effects of smoking with a sedentary life, which might explain her lower performance.

3.2. Posture and behavioral changes recorded on camera and symptoms described by the volunteers

According to literature, higher movement variability occurs with the development of muscle fatigue (Brown et al., 2016). Muscular and kinematic adaptations occur to reduce the load on the fatigued muscles (McDonald et al., 2016). Other studies concluded that fatigue-induced changes in movement strategies (Lee et al., 2014) and subjects altered their kinematic patterns significantly in response to muscle fatigue (Gates et al., 2011).

In order to confirm if any of these conclusions were also observed in the experiment, the recordings were analyzed.

As the experiment went on, the first noticeable changes were micro expressions (involuntary facial expressions), such as biting or narrowing lips during elevation and eyebrows down and together. These were signs that volunteers were starting to feel uncomfortable. An increase in breathing pattern also occurred, as verified by watching the recordings and also by the volunteers' testimony.

Volunteers started to change the way they executed the exercise by lifting and holding the load, in different ways than the initial. The load was meant to be lifted horizontally relative to the table. Some volunteers started to rotate the disk during the elevation and making it vertical to the ground, at maximum elevation. Others opted to sustain it from below, with the hands together and palms facing up. The ones that kept the hands in the intended position, started to tighten and release the fingers on the load, trying to get a better grip and also, enable some rest in each hand.

The movements started to be less fluid and while lowering the load, subjects increased eccentric movement speed, using gravity to help them lower the load.

At the start of the lifting and when they inverted lifting to lowering, subjects demonstrated increasing stooped position, as well, as slight head bending forward. When inverting lifting to lowering, subjects struggled to maintain their position.

Another aspect noticed was that people started bending their neck sideways, to relieve tension on the trapezius muscle and shoulders. They also rotated their shoulder from time to time.

Due to the fact that volunteers were standing still, they started decreasing their body stability and started balancing more. They started to hold their body on one leg and then changing to the other. The fact that some volunteers felt discomfort in the legs (numb legs), although the experiment only directly fatigued upper limbs, shows that there might be a correlation between upper and lower body. By standing still and frequently keeping the arms horizontally at shoulder level, this corresponds to static muscle work, which means that the blood requirement was higher than the supply. This follows the conclusions made by Oyewole (2014), because limited blood flow, delivers insufficient oxygen and nutrients. This means that when studying muscle fatigue, the whole body should be assessed together.

Subjects started noticing they were adopting a stooped position and started stretching their body and spine from time to time, in order to correct their posture and relief tension in their lower back.

In the final stages of the experiment, the movement started to be performed by lifting the load up to the chest and then moving it forward, instead of the gradual elevation and move away from the body. This strategy was used to compensate muscle fatigue and because lifting a load closer to the body is easier to perform.

As the experiment went on, some struggled to follow the metronome rhythm and started executing the movement in a very fast pattern, while others performed it slowly. This might indicate that people started losing focus.

Another important aspect is the fact that there were no external influences/incentives contributing to the subject's activity. Some volunteers expressed that they would probably do better if they were listening to music, or watching a video. Others suggested that more than one person should do the experiment at the same time, so they could talk and distract themselves. This might mean the psychologic component is also important, making mental fatigue influence physical performance. A recent systematic review conducted by Van Cutsem et al. (2017) assessed the effects of mental fatigue on physical performance. It concluded that mental fatigue impairs endurance performance and is mediated by a higher than the normal perception of effort.

Summing up, the posture and behavioral alterations observed in the recordings included:

a) Microexpressions (involuntary facial expressions) including biting or narrowing lips during elevation, eyebrows down and together;
b) Increased breathing pattern;
c) Changing the load support strategy (hand and wrist posture);
d) Tightening and releasing fingers on the load, trying to get a better grip;
e) Increase in eccentric movement speed, following the conclusion of Brown et al. (2016).
f) Increased forward bending, also described by Mehta et al. (2014);
g) Head slightly bending forward;
h) Neck bending sideways;
i) Decrease in body stability;
j) Changing support leg (some volunteers started to feel numb legs);

k) Stretching body and spine;
l) Holding load closer to the chest during elevation in the final stages of the experiment, resulting in a less fluid movement. This shows volunteers adapted to compensate fatigued muscles, which was also concluded by McDonald et al. (2016), Lee et al. (2014) and Gates et al. (2011);
m) Increased difficulty to follow metronome rhythm;

Symptoms described by the volunteers included discomfort in the wrists, brachioradialis, biceps brachii, triceps brachii, deltoids (anterior, medial and posterior), erector spinal muscles and gastrocnemius muscle.

3.3. Total execution time, Borg Scale, initial and final movements time

The total execution time, Borg Scale and initial and final movements time are presented in Table 3. The total time in the experiment of each participant, both males (M) and females (F), is presented in Figure 6, while Figure 7 presents the Borg Scale values, from 0 (none at all) to 10 (maximal exertion).

Table 3. Total time, Borg Scale, initial and final movements time

	t_{total} (s)	Borg Scale	t_i (s)	t_f (s)
Males	40.5 ± 15.8	4.3 ± 0.9	4.8 ± 0.4	5.0 ± 0.1
Females	18.3 ± 9.9	5.3 ± 1.9	5.0 ± 0.3	4.6 ± 0.7

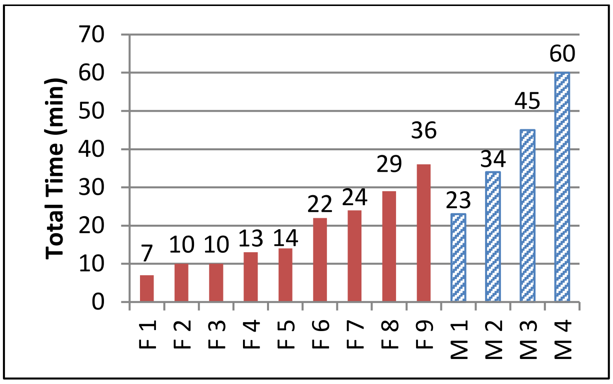

Figure 6. Total time in the experiment

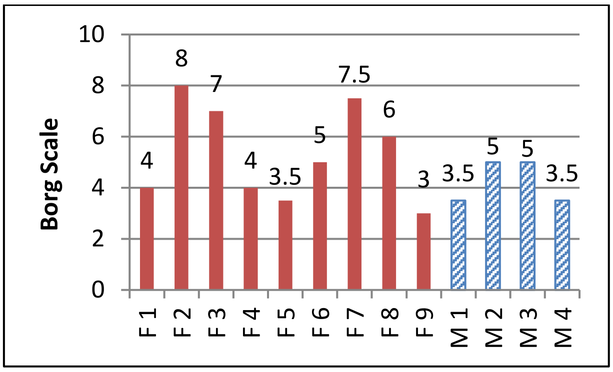

Figure 7. Borg Scale values

Analyzing Figure 6, it seems that the males could handle more time performing the experiment. Male 3 and 4 had the biggest times, with 45 and 60 minutes respectively. The 3rd biggest time belongs to female 9, with 36 minutes, followed closely by male 2 with 34 minutes. Female 1 had the lowest time, with only 7 minutes of exercise.

Subjects rated their level of fatigue on a scale from 0 (none at all) to 10 (maximal exertion) and the scores are presented in Figure 7. The highest scores were given by female 2, 3 and 7. Female 2 and 3 did the same time (10 minutes) and gave similar Borg scale results (8 and 7 respectively), corresponding to a really hard exercise. Female 7 gave a similar score and did the experiment for 24 minutes. Female 9 gave the lowest score and was the female that did the experiment for a longer time. On the other side, female 1 only gave a value of 4, half of female 2, which shows that it might not be self-aware of her fatigue level. In a work environment, this can lead to excessive effort and cause injuries. Male 1 and 4 gave the same score, although male 4 lasted three times more in the exercise.

3.4. Statistical Results

The statistical results, namely the Student's paired t-test, of the wrists, elbows, and shoulders are presented in Figure 8, Figure 10 and Figure 13, respectively. The dashed line boxes mark the lowest p-values obtained in terms of position, velocity, and acceleration.

A. Wrists

Figure 8 analysis can be divided into the following parts:

1) Wrists range (position) on the X axis (Range of motion):

In order to test the hypothesis of forwarding bending increase and assess if participants lifted the load in a stooped posture that they bent more over time, as concluded by Mehta et al. (2014), the highest position values in the X-axis were analyzed.

The normality tests showed that the results followed a normal distribution because the p-values (bilateral) were greater than the significance level (alpha = 0.05).

In the Student's paired t-test results, as shown in Figure 8, the calculated p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.47 and L Wrist = 0.95), meaning that the initial hypothesis “The difference between the means is equal to 0” shouldn’t be rejected. This means that no significant differences were observed in the wrist range mean in the X-axis.

The results demonstrated that the individuals increased their wrist range on the X-Axis. Overall, the right wrist displayed more changes in terms of interquartile range, which translated to a much more concise pattern of the volunteers, probably because only 1 person was left handed. Right-handed people might command that hand with more intensity and support more weight, in order to get higher stability, while their left hand is used for balance.

2) Wrists 3D Position

The highest 3D position values were analyzed because they occurred at the inversion point between lifting and lowering. The data followed a normal distribution.

Analyzing the p-values, no significant differences were observed in the wrist 3D position means before and after. The right wrist displayed more changes (lower p-value).

3) Wrists 3D Velocity

In order to compare the lifting and lowering stages, the velocity analysis was divided into two sections. In both stages, the data analyzed was the highest velocity value verified.

Starting with the lifting stage, male 2 was removed in order to have a normal distribution. The calculated p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.79 and L Wrist = 0.60), meaning that no significant differences were observed in the wrist 3D velocity means before and after.

The left wrist had a more prominent alteration when compared to the right wrist (lower p-value). This translates into a higher variability of velocity values on the non-dominant hand. The reason might be that the right wrist is more controlled and needs to be more stable and regular in the movements. Nonetheless, the results showed that both wrists increased their velocity, although some people decreased it.

On the lowering stage, female 7 was removed in order to have a normal distribution. No significant differences were observed in the wrist 3D velocity mean before and after, but the right wrist had lower p-value.

The results showed that the lowering velocity increased. This follows the conclusions made by Brown et al. (2016) that stated that there could be an increase in eccentric movement speed since the muscle cannot resist the gravitational force.

4) Wrist 3D Acceleration

The p-value (bilateral) for both wrists was greater than the significance level alpha = 0.05 (R Wrist = 0.21 and L Wrist = 0.28), meaning that no significant differences were observed in the wrist 3D acceleration mean before and after. The right wrist demonstrated higher differences due to a lower p-value.

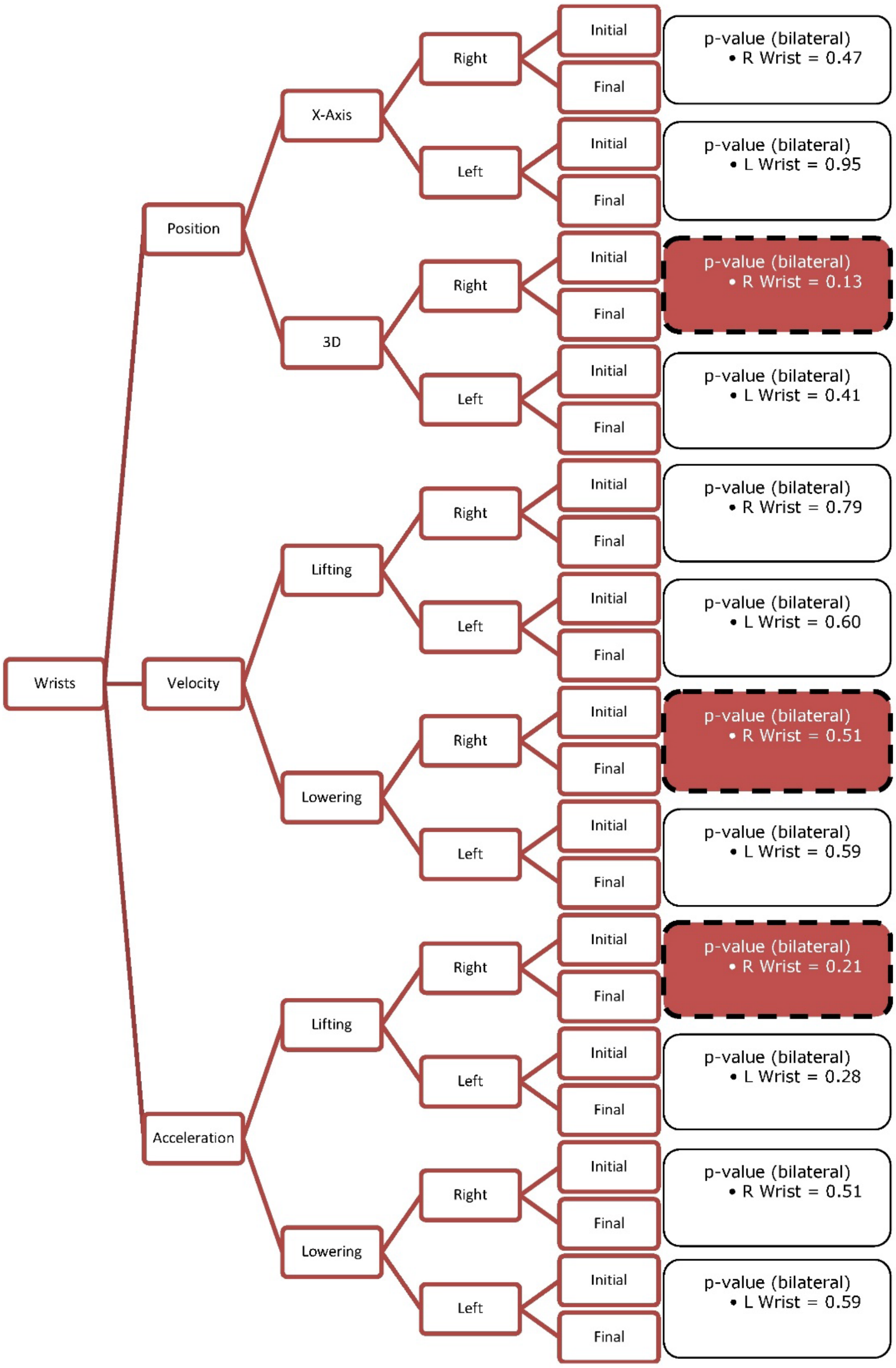

Figure 8. Wrists student's paired t-test results

Figure 9 shows differences in the right and left wrists, in the initial (I) and final (F) movements. In the right wrist, the first quartile and the median decreased, while the mean and third quartile increased. On the other side, the left wrist only had the same pattern with the first quartile, since it increased the median, and decreased the mean and third quartile.

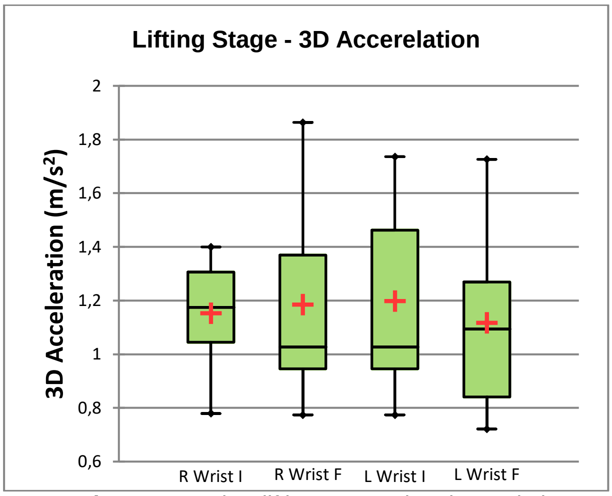

Figure 9 – Wrists lifting 3D acceleration variation

Half of the volunteers had lower acceleration variability in the final movement, with only maximum and minimum accelerations differing around 1 m/s2, while the other half increased that difference. The half that increased had less fluid movement, with higher acceleration values in some parts and lower values in others.

In the lowering stage, Grubbs test identified female 7 as an outlier and it was removed in order to have a normal distribution. No significant differences were observed in the wrist 3D acceleration means before and after.

The variation in acceleration values increased on both wrists. This complements the conclusion of the velocity results where volunteers had a higher eccentric movement speed. Comparing the values, the mean value in the lifting stage was 1.16 m/s2 and 1.21 m/s2 in the lowering stage, meaning that the lowering stage had higher variation, since the volunteers would drop the load with the help of gravity, and not lower it carefully and in a sustained way.

B. Elbows

Figure 10 analysis can be divided into the following parts:

1) Elbows Z-Axis Range

All the 13 volunteers were included. The results followed a normal distribution.

No significant differences were observed in the elbow Z-Axis means before and after.

The results showed that volunteers didn't open more the arms, but the other way around, they closed the elbows and hold them near the body, in order to increase stability and hold the load better.

2) Elbows 3D Velocity

In order to compare the lifting and lowering stages, the same strategy used for the wrists was applied, that is, the velocity analysis was divided into lifting and lowering.

In the lifting stage, all subjects were included and a normal distribution was verified.

The p-value (bilateral) for the right elbow was greater than the significance level alpha = 0.05 but not the left elbow (R Elbow = 0.43 and L Elbow = 0.04), meaning that in the left elbow there was a significant difference in the 3D velocity mean before and after.

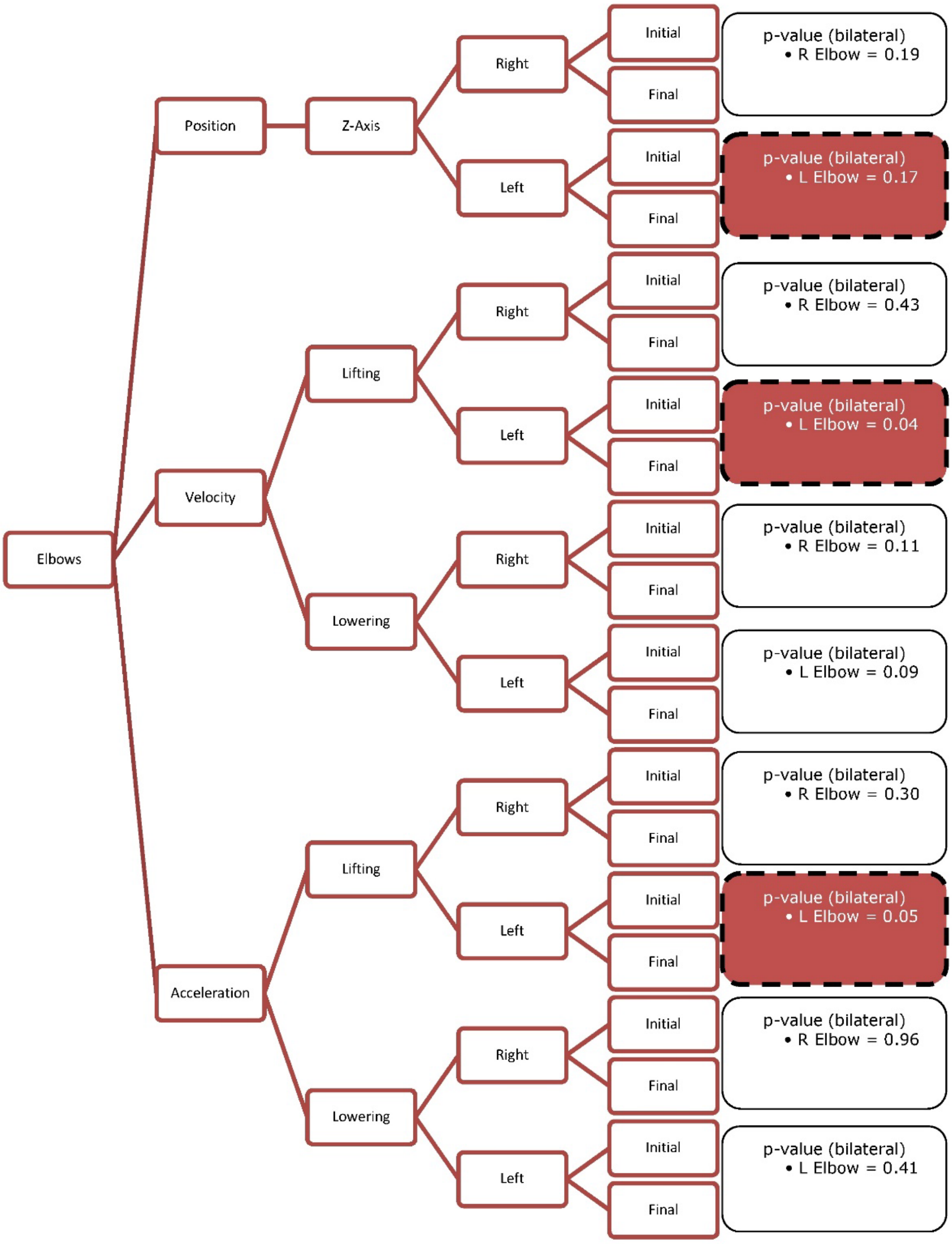

Figure 10. Elbows Student's paired t-test results

Observing Figure 11, that difference is noticeable. Comparing both elbows, they increased interquartile range, third quartile, and range between maximum and minimum. While the right elbow almost didn’t change median, on the left elbow it rose from 0.44 to 0.52 m/s. The results indicate that volunteers performed the lifting with higher velocity in the final movement of the experiment, especially on the left elbow. The same conclusion was made with the wrists, also with more evidence on the left side. This means that both left wrist and elbow had higher differences from beginning to end.

In the lowering stage female 7 was removed in order to obtain a normal distribution. No significant differences were observed in the elbow velocity mean values.

The results demonstrated that the lowering movement was performed with higher velocity, following the same idea of the wrists and the conclusions made by Brown et al. (2016).

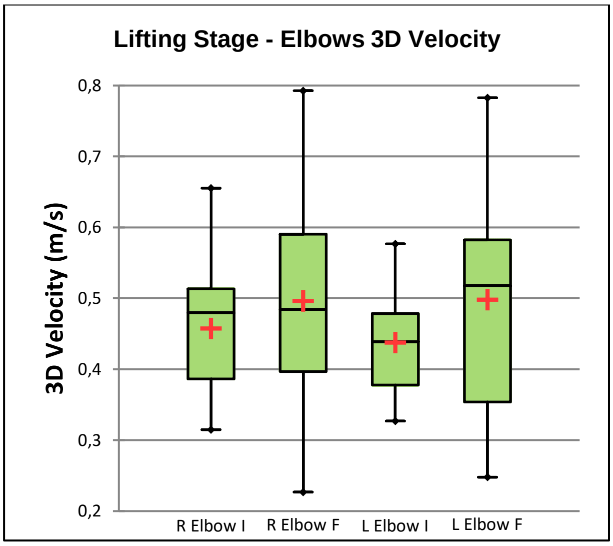

Figure 11. Elbows Lifting 3D Velocity

3) Elbows 3D Acceleration

In order to compare the lifting and lowering stages, the acceleration analysis was divided into 2 sections.

Analyzing the p-value (bilateral) for both elbows, the left elbow had the alpha value, meaning that the differences were significant.

Observing Figure 12, both elbows increased the mean, median, third quartile, interquartile range, and maximum value. This means that in the last movement, the difference between the minimum and maximum acceleration values increased, translating into more impulsive movement.

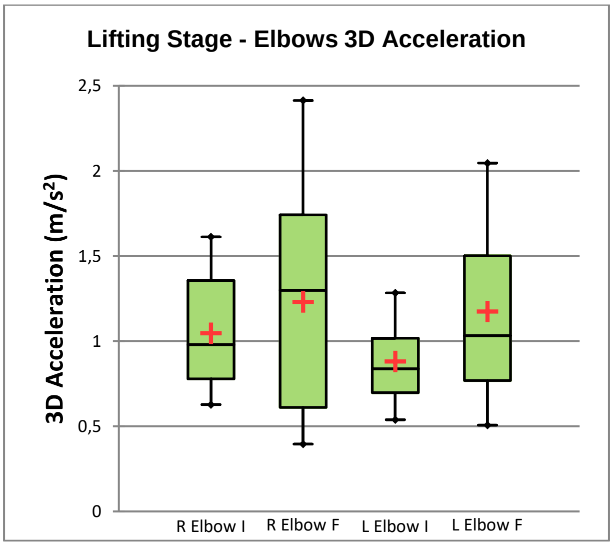

Figure 12 – Elbows Lifting 3D Acceleration

C. Shoulders

1) Shoulders 3D Position

As shown in Figure 13, the p-value (bilateral) for both shoulders were greater than the significance level alpha = 0.05 (R Shoulder = 0.27 and L Shoulder = 0.11), meaning no significant differences were observed in the shoulders position mean values.

The results showed an increase in 3D position values and it was mostly contributed by an increase in the X and Y axis values, which correspond to a stooped position, both at the beginning/end of the movement and at the maximum arm extension in the sagittal plane.

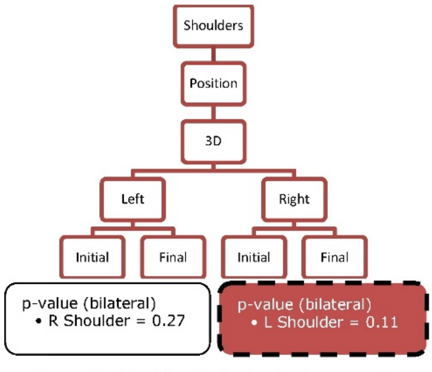

Figure 13 – Shoulders Student's paired t-test results

4. CONCLUSIONS

The questionnaires results showed that there is a slight tendency for people that practice sports to have more endurance. On the other side, the lack of exercise and smoking might harm the physical condition.

In order to compensate for muscle fatigue, people adapted their working strategy and exhibited several muscle fatigue indicators. Males could handle more time performing the experiment.

The statistical analysis showed that individuals increased their range on the X axis (increased forward bending), both wrists increased their velocity in the lifting and lowering stage. In terms of acceleration, half the participants had less fluid movement during lifting, with higher acceleration values in some parts and lower values in others. Relatively to the elbows, subjects closed the elbows and hold them near the body, in order to increase stability and hold the load better. Volunteers performed the lifting with higher velocity in the final movement of the experiment, especially on the left elbow. Both left wrist and elbow had higher differences from beginning to end than the right side.

4.1. Strengths of the methodology

This methodology is a new approach that allows the assessment of common symptoms and behaviors that people demonstrate when starting to feel muscle fatigue, which could be listed and used as indicators in the work environment.

Motion analysis can be combined with accelerometry in order to assess muscle fatigue, by noticing changes in accelerations and movement patterns, as well as angles between wrist, shoulder, and elbow.

A specific checklist could be created for each type of work, by performing a pilot test with some volunteers and analyzing the recordings. That way, a list of indicators could be used in the future, to enable a quick assessment of the worker's physical condition.

4.2. Limitations of the methodology

The main limitation of this study is the fact that only the first and last movements of lifting and lowering were studied, because the video analysis was made manually by marking each reference point placed on the volunteer body in each frame of the video (1 frame = 0.03 s), which made it impossible to assess the entire recordings. The gradual development of muscle fatigue and registered symptoms were only described and not quantified.

The ideal solution would be the continuous analysis of the recordings, with automatic live results, that allowed a fast assessment of the situation.

The analyzed sample of 13 people is not the ideal sample size to generalize the results and future work should include a larger and representative sample.

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