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*Research Article*

# Acute Effects of Muscular Fatigue on Vertical Jump Performance in Acrobatic Gymnasts, Evaluated by Instrumented Insoles: A Pilot Study

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The study of fatigue during training is becoming a very useful tool to avoid possible injuries not only during the training sessions but also during recovery time. Many researches have proved that concepts such as muscular fatigue and postactivation potentiation have a close relationship. With this aim, vertical jump can provide a very important information that can help to analyze the muscular fatigue that happened during this type of activity, mainly if the monitoring system is able to measure jumping parameters during their regular training session in their natural training environment. This study was performed with instrumented insoles called ECnsole. These insoles were tested with a group of twelve volunteers. In a tumbling surface, the participants performed a jumping protocol in three conditions: rest, fatigue-induced, and recovery. Using these validated insoles, the acrobatic gymnasts showed an inability to use the stretch-shortening cycle for improving vertical jumping performance after fatigue condition, although no deterioration of jump performance was found.

## 1. Introduction

The practice of acrobatic gymnastics is a growing physical activity; consequently, the injuries related are also increasing [1]. Acrobatic sports are characterized by a high level of body control in several positions both on and off the ground, which requires various motor skills [1]. Gymnast performance is related to jumping capacity, especially in floor and jumping routines [2]. Moreover, the gymnastics exercises involve demanding footwork on several surfaces, for example, hardwood floors, gymnastics mats, and trampolines [3].

The jumping performance depends on the coordination of the segmental movements, which is determined by the interaction between the neuromuscular indicators and the net moments that have to be generated around the joints to accomplish the mechanical demands [4]. During training and competition, gymnastics athletes perform a large number of jumps that involve the stretch-shortening cycle (SSC) of muscles, which results in acute muscle fatigue of the legs [2, 5]. Among factors influencing the muscle response are the muscle fatigue and potentiation as well as the recovery process, which are provided by the coaches with a more accurate idea about the muscle condition [2]. The phenomenon "post-activation potentiation" (PAP), induced by a voluntary contraction, as conditioning activity, and indicates to a significantly enhances muscular power as a result of previous muscular work [6, 7]. After a conditioning activity, the mechanisms of muscular fatigue and PAP coexist, and therefore, subsequent power output and performance depend on the balance between these two factors [8]. Although it is necessary to clarify that unlike PAP, changes in muscle temperature, muscle/cellular water content, and muscle activation could cause voluntary force enhancement, which is called as postactivation performance enhancement (PAPE) to distinguish it from PAP, that has been largely explained by an increased myosin light chain phosphorylation occurring in type II muscle fibres [9]. Gymnasts who are able to recover more efficiently between a series of skills are more likely to sustain a higher level of performance and to reduce their risk of injury through fatigue [10].

From a neuromuscular point of view, the fatigue is defined as an exercise-induced reduction in maximal voluntary muscle force and may be due to peripheral changes at the level of the muscle, but also at the level of the central nervous system, rest reverses it [11]. This concept overlooks competing intramuscular mechanisms that potentiate force during strenuous workouts and refers more precisely to a total reduction of performance. Fatigue can be evaluated by quantifying maximal voluntary force, maximal voluntary shortening velocity, or power [11]. The height of a vertical jump, especially in the countermovement jump (CMJ), is commonly used to evaluate the legs muscular power [12] and to detect neuromuscular fatigue [13]. In addition, vertical jump has been used in several studies investigating the recovery time after fatigue interventions; however, further research is needed to elucidate the most relevant variables to analyze fatigue when the vertical jumps are employed [11].

The complexity of gymnastics' events requires several fitness tests in order to monitor the individual progress, for example, the jumping test [14]. Vertical jump tests are employed to assess neuromuscular function, using a variety of instruments and assessment protocols [15] such as force platform, contact mats, accelerometers, and optical devices. However, although laboratory tests provide a high level of accuracy, a more portable and compact approach could also be very useful to analyze jumping performance in the gymnasts. We are referring to minimally invasive systems capable to provide information from multiple sensors for a more complete assessment of jumping. In fact, the purpose of this investigation was to obtain data that could provide information about acute effects of muscular fatigue on vertical jumping performance in acrobatic gymnasts with the least influence in this performance by using an instrumented insole designed by our research group [12]. The authors hypothesised that an increase of external load would change jumping performance during a typical Bosco protocol [16] in acrobatic gymnasts.

## 2. Materials and Methods

*2.1. Participants.* A set of twelve volunteers participated in this study, all of them males (age: $20.7 \pm 3.9$ years, height: $169.7 \pm 6.7$ cm, weight: $65.1 \pm 7.2$ kg, and body mass index (BMI): $22.4 \pm 2.5\ kg/m^2$). All of them were acrobatic and sport gymnasts of Acróbatos Gymnastic Club (Granada, Spain) of different levels (from amateur to elite athletes). They were physically active due to their training sessions which were usually four times per week and in the six months before the study had no history of injury. The study was conducted during the competitive season. Written informed consent was obtained from all participants before starting the study, and the protocol was approved by the University of Granada Ethics Committee and met the requirements of the Declaration of Helsinki and the ethical standards in sports and exercise science research [17].

*2.2. Materials and Testing.* During the current study, a version of an instrumented insoles previously developed by the research group was used, called ECnsole, shown in Figure 1 [12, 18]. The instrumented insoles contained four pressure sensors Flexiforce A401 (Tekscan, South Boston, MA, USA) located at the big toe, first and fifth metatarsal heads, and the heel. These sensors had a diameter of 25.4 mm and a pressure range from 0 to 111 N. In addition, instrumented insoles contained a digital accelerometer LSM303D (STMicroelectronics, Geneva, Switzerland) placed in the arc of the foot; these sensors are communicated by means of the I2C protocol. The insole had a slim profile of 1 mm; therefore, any possible influence on jumping or any kind of exercise performance is minimized. They are connected to a datalogger unit which is placed at the lower back to permit the athletes to carry out the test properly. The datalogger is a microcontrolled unit that uses a PIC24FJ256GB106 (Microchip Technology Inc., Chandler, AZ, USA) to acquire signal from both analog and digital sensors. The gathered data can be stored into a $\mu$SD card or sent them by means of a MiWi® transceiver to a personal computer. The measurement can be started either from remote order or by pressing a button located at the unit. The sampling frequency of the ECnsole system has been improved to reach 330 Hz compared to previous versions. ECnsole system is supplied by one 14500 rechargeable battery. This type of battery provided 1400 mAh at 3.7 V, with the same size as an AA alkaline battery. The autonomy of the system is seven and a half hours. In addition, an application has been developed in MATLAB (MathWorks, Natick, MA, USA) to receive the data from sensors and provided the research a user-friendly interface to analyze and plot data. The instrumented insoles have been already validated to measure vertical high jumps comparing its results to a gold standard [12]. The variables provided by the instrumented insoles were the flight time (in milliseconds), the pressure at jumping and landing instance (in kilopascal), and the accelerometer values (in g). Knowing gravity acceleration, the height jump can be calculated from the flight time [12].

The jumping protocol was performed into the tumbling surface. Tumbling surface is a type of "floor," which is 25

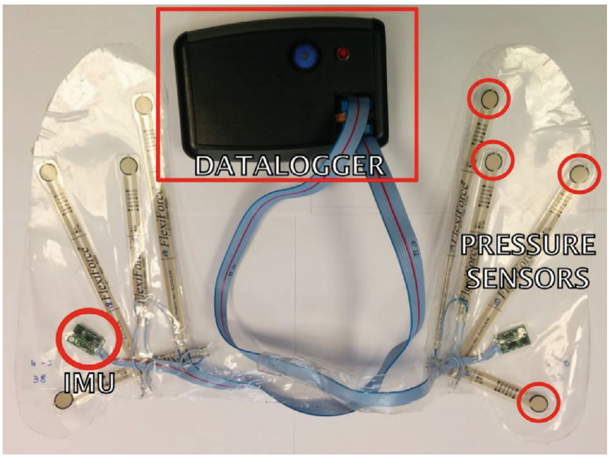


FIGURE 1: Picture of the instrumented insoles (ECnsole) pointing out the pressure sensors (four for each foot), the inertial sensors IMU, and the datalogger unit which is attached to the participant's waist.

meters long by 2-meter-wide track consisting of fiberglass rods under two layers of foam mats.

*2.3. Procedures.* At the beginning of the experiment, participants received comprehensive instructions and learned the proper technique of each jump test. Then, all participants completed ten minutes of warm-up exercises. Typical warm-up consisted of five minutes of low intensity running and five minutes of general exercise (i.e., skipping, leg lifts, lateral running, and front-to-behind arm rotations) and practicing the jump tests at low/moderate intensity. After completing the warm-up, the participants put on the trainers with the ECnsole system. The research group provided the same trainers to all the participants to avoid differences due to the footwear. Moreover, a prior familiarization with the jumping tests according to the protocol described by Bosco was carried out [16].

The experiment comprised three experimental sessions per participant as depicted in the flow chart of Figure 2. In each session, the gymnast had to perform five types of jumps: squat jump (SJ), countermovement jump (CMJ), Abalakov Jump (ABK), drop jump (DJ), and repeated jump (RJ). During SJ performance, the participant starts from a 90° knee-bent position with both hands on the hips. In the CMJ, the participant stands upright also with both hands on the hips, and then a countermovement is performed till it reaches approximately 90° to obtain impulse for jumping execution. In ABK jump, the participant stands with a knee angle of 180°, in this case, he or she can swing the arms back behind the body while the knees are bent at 90°. DJ consists in sinking from a platform elevated 60 cm above the floor, and once the floor is reached, jump energetically and finally absorb the reception. RJ is basically the same preceding that CMJ but repeating as many times as possible during 15 seconds.

The different experimental sessions in which the whole study was divided:

*PreTest:* after the warm-up, the participant started doing the five jumps already described in this work. Every jump was repeated three times except the RJ. When this session was finished, a training protocol designed to produce fatigue in the low body trunk started. The training consisted of 12 series of 6 forward tucked somersaults, with 10 seconds between somersaults and 2 minutes between series. This protocol was done on the tumbling surface

*PostTest:* immediately after the training protocol was done, the gymnasts repeated the same 5 types of jumps that in PreTest. Once they finished all the jumps, they rested for 15 minutes

*ReTest:* this session corresponded to the last repetition of the jumps after the resting time of 15 minutes.

*2.4. Statistical Analysis.* Data were analysed using SPSS, v.19.0 for Windows (SPSS Inc., Chicago, IL, USA), and the significance level was set at $p < 0.05$. Descriptive data are reported in terms of means and standard deviations (SD). The differences between jumping performance in the jump protocols were analysed using analysis of variance (ANOVA) of repeated measures, adjusted by the Bonferroni test. Additionally, effect sizes for measurements differences were expressed as Cohen's d [18]; effect sizes are reported as trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) [19].

## 3. Results and Discussion

In Figure 3, an example of the data obtained from instrumented insoles by performing one of the ABK jumps has been depicted. The four pressure sensors are plot in the graph. Despite all the sensors were measured during the experimental test, only the big toe sensor was considered into the statistical study because in all jumps performed, it was the last sensor contacting the ground before the jump started and the first sensor in contact with the ground in the landing.

In Figures 4 and 5, no significant differences were found between the tests within each of the jumps for flight times, jump height, and jump accelerations, respectively. However, in accelerations at landing, there is a significant difference between pretest and retest in RJ ($-4.99 \pm 1.30\,\mathrm{m/s^2}$ vs. $-5.88 \pm 1.14\,\mathrm{m/s^2}$, respectively, $p < 0.001$, Cohen's $d = 0.760$) (Figure 5). Moreover, there are significant differences in the pressure at jumping instance, between the PreTest and ReTest in the CMJ ($4.89 \pm 0.41$ kPa vs. $3.87 \pm 0.36$ kPa, respectively, $p = 0.008$, Cohen's $d = 2.761$), in the ABK ($5.03 \pm 1.65$ kPa vs. $3.92 \pm 1.43$ kPa, respectively, $p = 0.006$, Cohen's $d = 0.750$) and between PreTest and Postest in the RJ ($3.61 \pm 1.24$ kPa vs. $2.85 \pm 1.15$ kPa, respectively, $p = 0.006$, Cohen's $d = 0.663$) (see Figure 6).

The purpose of this investigation was to collect data in order to determine acute effects of muscular fatigue on vertical jumping performance in acrobatic gymnasts using an instrumented insole under an environment that do not affect both jumping performance and gymnast convenience. The main finding of this study was that muscular fatigue did not show a significant influence on jumping performance in these athletes, only, a significant change in pressure at jumping in RJ was found. In addition, the PAPE phenomenon did not occur. However, a previous study in young gymnasts showed that several condition stimuli induce a PAPE

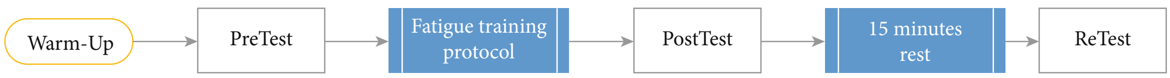


Figure 2: Flowchart of the complete undertaken experiment.

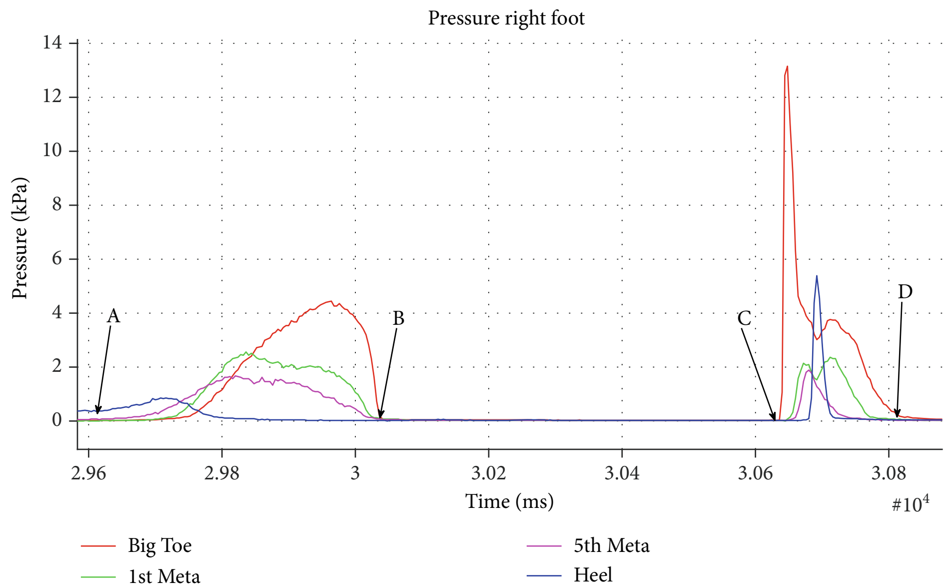


Figure 3: Example of ABK jump data obtained by ECnsole. At instant A, the participant started arm swinging to get an impulse for the jump. The moment B represents the beginning of the jump until the reception with the group represented in C. From that instant to D, the participant absorbed the jump till resting in standing up position.

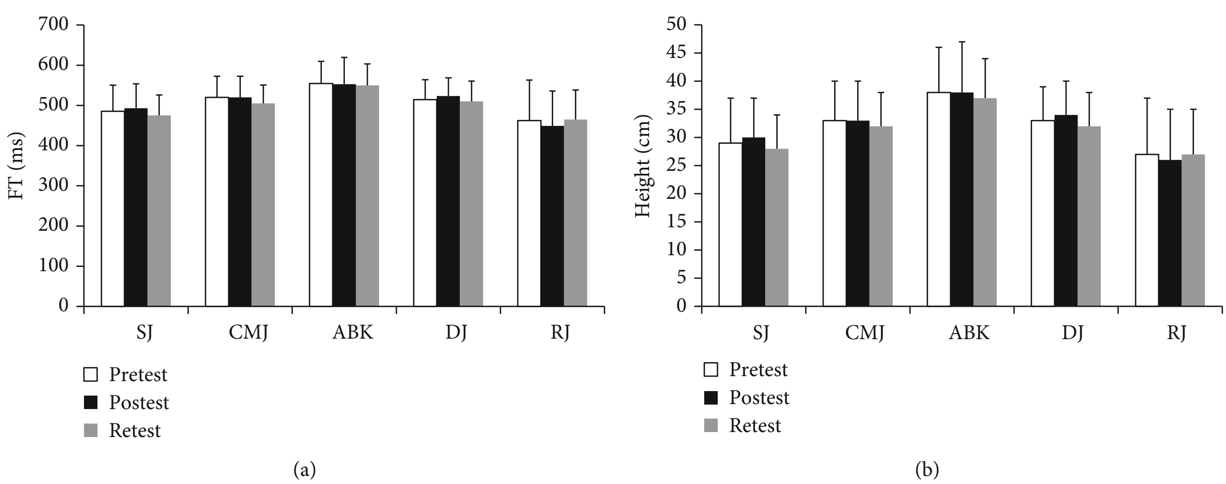


Figure 4: Flight times (a) and heights (b) in the jumping protocol.

response resulting in an improvement in DJ height in the acute phase of recuperation (15 sec–9 min) [20]. In this regard, in elite gymnasts, one set of 5 tuck jumps during warm-up is not adequate to increase CMJ performance, while 3 sets of 5 tuck jumps result in a relatively large increase in CMJ performance [21]. However, heavy-loaded stimulation results in decreased musculature performance and induces the fatigue effect [22, 23]. Moreover, recovery duration after a heavy-load exercise might influence this balance between PAP and fatigue; also, it seems that PAP depends on individual strength levels, which requires different recovery periods [24]. In a meta-analysis, Jacob et al. noted that PAP was optimal after multiple (vs. single) sets, performed at moderate intensities, and during moderate rest periods lengths (7–10 minutes).

On the other hand, leg stiffness is a relevant property in the performance of running, jumping, and hopping activities [25] and has been reported that SSC fatigue induces changes in knee stiffness and take-off velocity during DJ [26]. The increased stiffness during fatigue can be considered as a

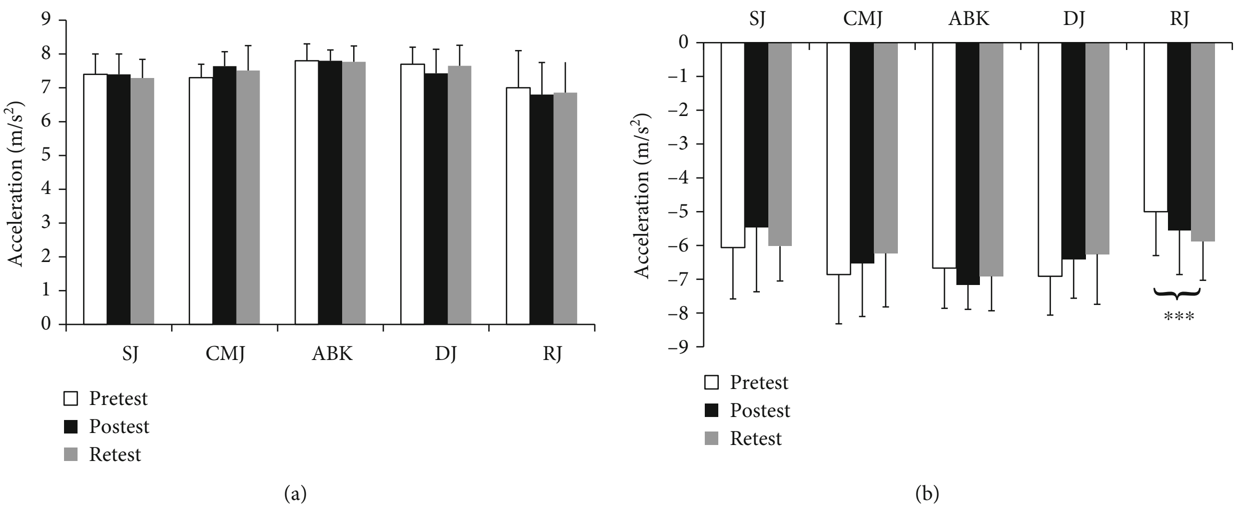


Figure 5: The acceleration at jumping (a) and landing (b) instances in the jumping protocol ($^{***}p < 0.001$).

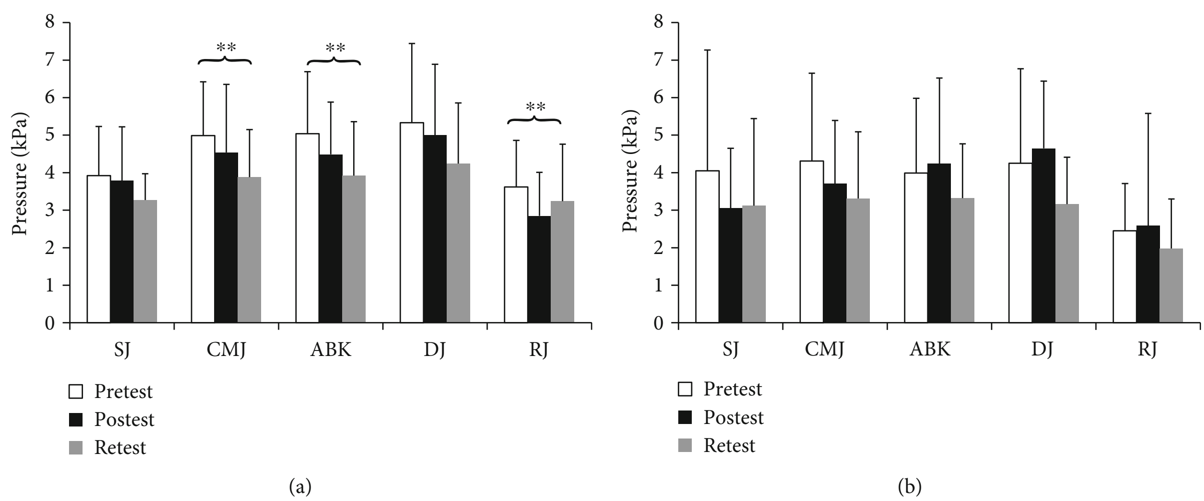


Figure 6: The pressure at jumping (a) and landing (b) instances in the jumping protocol ($^{**}p < 0.01$).

way the muscle compensates for the lost contractile performance when it performs the SSC [27] in a way used in the present study. Therefore, the optimally use of leg stiffness could store more elastic energy at landing and produce high levels of concentric force output at jumping, which could reduce the fatigue and increasing jumping performance.

## 4. Limitations and Conclusions

Although in the current study, there was a reduction in the pressure at jumping in CMJ, ABJ, and RJ and an increase of acceleration at landing in RJ during experimental protocol, leg stiffness could have increased, keeping the jump height unchanged despite fatigue. However, leg stiffness was not registered in the current study. The main limitation in this study was that fatigue levels or internal load were not recorded; future studies should address it. However, the strengths of this study include a population sample of elite acrobatic athletes, and we used a novel device to analyze the Bosco protocol in a real setting.

Therefore, the findings of the current study suggest that the experimental protocol, in relation to loading and recovery, was not effective to induce an imbalance between PAPE and fatigue. From a practical point of view, the employed of an instrumented insole could monitor jumping performance in a portable and compact ecological setting. In conclusion, the acrobatic gymnasts showed an inability to use the SSC for improving vertical jumping performance after fatigue condition, although no deterioration of jump performance was found.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

## Authors' Contributions

Fernando Martínez-Martí and Pedro A. Latorre-Román contributed equally to this work.

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