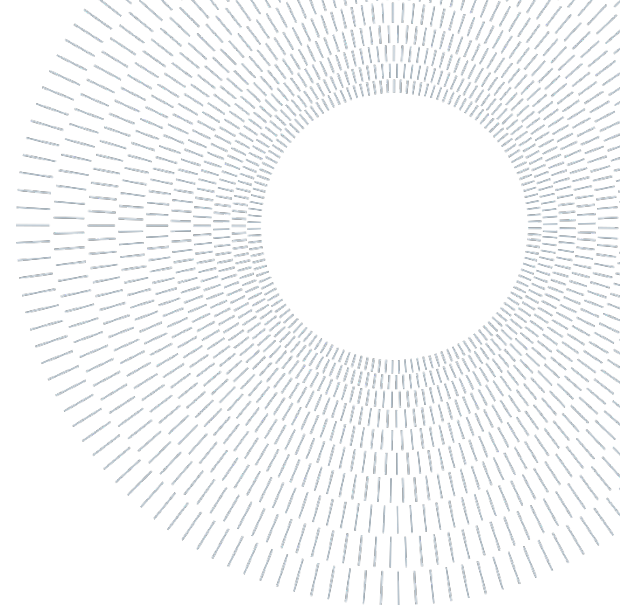




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EXECUTIVE SUMMARY OF THE THESIS

# L'impatto dell'attività sportiva sul cammino e sulla stabilità posturale in età giovanile: analisi comparativa tra soggetti agonisti, ex-agonisti e sedentari

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

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## 1. Introduction

According to the World Health Organization (WHO), physical activity produces beneficial effects on individual health, as widely demonstrated by numerous studies in the scientific literature. However, approximately 27.5% of the adult population and about 81% of adolescents worldwide do not meet the previous physical activity guidelines proposed by the WHO in 2010, leading to an increased risk of developing cardiovascular and musculoskeletal disorders. To address this issue, the WHO has set the goal of reducing global physical inactivity by 15% by 2030, as outlined in the *Global Action Plan on Physical Activity*<sup>1</sup>.

Several scientific studies have shown that regular participation in sports leads to positive adaptations in the body's main physiological systems. Since these systems are closely interconnected, it is particularly interesting to integrate the study of

physiological changes induced by physical activity with the analysis of their impact on two fundamental motor functions of daily life: gait and postural stability.

Gait requires the integrity and coordination of all levels of the nervous system and the proper functioning of the musculoskeletal structures, making it a complex and highly integrated activity<sup>2</sup>. Similarly, postural stability represents a complex neuromuscular task involving the cooperation of the central and peripheral nervous systems, the musculoskeletal system and the sensory system<sup>3</sup>. These functions are widely studied in the clinical field—particularly gait—through a multifactorial assessment that includes various analyses supported by specific indices. However, although many studies in the literature have examined the effects of sports on postural stability through different experimental protocols, gait analyses are mainly conducted in clinical contexts, thus revealing a gap in the literature

concerning the potential effects of physical activity on gait quality in young healthy populations.

## 2. Aim of the thesis

With regard to what was discussed in the introduction concerning the lack of studies investigating the impact of sports participation on gait in everyday conditions, this thesis project aimed to provide preliminary evidence on how sport may influence locomotion, highlighting potential modifications in gait patterns. Moreover, although the literature offers numerous findings on the effects of sports practice on postural control, both in static and dynamic conditions, there is a lack of studies examining postural stability in former high-level competitive athletes who have ceased their sporting activity.

Based on these considerations, the present study pursued two main objectives: the first was to provide evidence of the beneficial effects of continuous sports practice by comparing athletes and sedentary individuals in terms of gait and postural control, both in static and dynamic conditions; the second was to investigate the potential residual benefits of sport over time, highlighting possible motor adaptations that may persist as a memory of prior sport activity.

## 3. Materials and methods

Thirty participants between 18 and 35 years of age were recruited for the study. The sample was evenly divided into groups of five: male athletes (age:  $24 \pm 2$ ; BMI:  $21.69 \pm 2.12$ ), male former athletes (age:  $24.6 \pm 0.89$ ; BMI:  $21.78 \pm 1.35$ ), male sedentary individuals (age:  $24 \pm 1.41$ ; BMI:  $22.27 \pm 1.56$ ), female athletes (age:  $23.6 \pm 2.67$ ; BMI:  $21.71 \pm 2.14$ ), female former athletes (age:  $22.8 \pm 1.3$ ; BMI:  $21.14 \pm 2.08$ ) and female sedentary individuals (age:  $22.2 \pm 1.3$ ; BMI:  $21.15 \pm 2.54$ ). The experimental activities were conducted at “Human Performance Lab” (Politecnico di Milano, Polo territoriale di Lecco). Each subject read and signed a written informed consent, resulting from the approval by the Ethics Committee (n. 76/2024). Then specific anthropometric parameters were measured on each participant (body mass, height, pelvic width and height, lower limb length). Each participant was then equipped with reflective optical markers according to the Helen Hayes protocol and fitted with eight surface EMG electrodes to bilaterally

assess the tibialis anterior, medial gastrocnemius, rectus femoris and semitendinosus muscles.

This study was conducted by means of eight infrared cameras (SMART EVO), two force platforms (P-6000) and surface electromyography (FREE EMG 1000), provided by BTS Bioengineering SpA (Garbagnate Milanese, MI).

The experimental protocol included: maximal voluntary contraction (MVC) for each muscle; six valid gait trials; three bipedal standing trials with eyes open and three with eyes closed (60 s each); three single-leg standing trials with eyes open (60 s) and three with eyes closed (30 s); three tandem standing trials with eyes open (60 s); three Single Leg Hop Stabilization Test (SLHS) trials in the anterior and three in lateral directions; and three modified Star Excursion Balance Test (mSEBT) trials.

For each participant, from the gait trials, spatiotemporal parameters over six gait cycles were extracted, and symmetry indices between the right and left limbs were computed. Joint angles of the trunk, pelvis, and hip in all three planes, as well as knee flexion–extension, ankle dorsiflexion–plantarflexion, and foot progression angles along the gait cycle, were also obtained. In addition, gait quality indices – Gait Deviation Index (GDI), Gait Profile Score (GPS), and Gait Variable Score (GVS) – were computed. As for joint dynamic parameters, joint moments and powers for the ankle, knee, and hip in the sagittal plane were extracted, along with ground reaction force patterns. Muscle activation timings were obtained to analyse activation patterns and frequencies across the different groups.

From the postural stability tests, both time- and frequency-domain analyses of the Centre of Pressure (COP) were performed. Time-domain parameters included sway area, total COP path length and directional path lengths, maximal excursions and mean COP velocity. Frequency-domain parameters included PF50 and PF95, total and directional power. Total power was computed using Welch PSD (Power Spectral Density) with COP in cm; since PSD units are  $\text{cm}^2/\text{Hz}$ , total power is reported in  $\text{cm}^2 \cdot \text{s}$ . Also, the percentage contribution of sensory systems was calculated from total power across frequency bands associated with visual ( $<0.1$  Hz), vestibular (0.1–0.5 Hz), somatosensory (0.5–1 Hz), and neuromuscular (open-loop) control ( $>1$  Hz).

Romberg indices were also calculated to evaluate the effect of visual removal. For the mSEBT, flexibility and postural control were assessed using the normANT(%), normPL(%), and normPM(%) indices, defined as the normalized reached distances in the anterior, posterolateral, and posteromedial directions relative to the length of the moving limb.

A hierarchical approach was adopted for the statistical analysis. As illustrated in the following figure (Figure 1), in the gait trials and in the single-leg standing tests, the presence of differences between the right and left limb was first assessed; in the absence of asymmetries, differences between males and females were then evaluated. When no significant sex-related differences were found, the data were aggregated into three main categories (athletes, former athletes, and sedentary individuals). Once the groups were defined through these preliminary analyses, the appropriate statistical tests for the stability assessments were applied following the same hierarchical approach, while the kinematic and dynamic curves were analysed using Statistical Parametric Mapping (SPM) with an independent-samples t-test, given the data normal distribution.

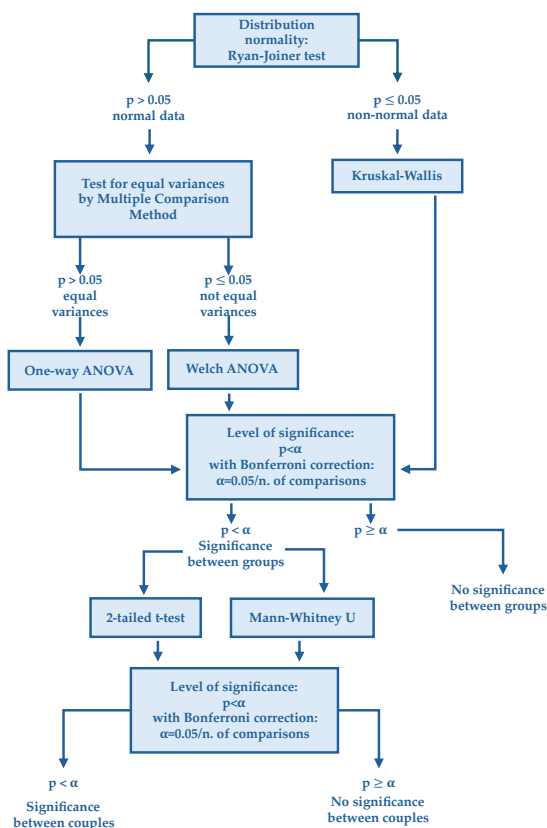


Figure 1 Flowchart of the hierarchical approach adopted for the selection of statistical test

## 4. Results

From the gait analysis and the SPM results, no significant differences emerged among the female categories, whereas marked variations were observed in the male subjects, particularly when comparing non-athletes with athletes and former athletes. Specifically, male non-athletes showed a greater external hip rotation throughout the gait cycle, with a peak of about  $15^\circ$  at toe-off; the SPM confirmed significant differences compared to non-athlete and former-athlete females ( $p < 0.008$ ). During the swing phase, these subjects also exhibited greater hip abduction than the other groups. At the knee, male non-athletes presented reduced flexion during the loading response, with an average peak of  $7^\circ$ , compared to the  $15^\circ$ – $18^\circ$  observed in the other groups, a difference supported by the SPM ( $p < 0.008$ ). Finally, foot progression showed a pronounced external rotation throughout the cycle, with a peak of  $24^\circ$  during the mid-swing phase, higher than the angles recorded in the other categories ( $15^\circ$ – $20^\circ$ ). The SPM also confirmed significant differences in this parameter ( $p < 0.001$ ).

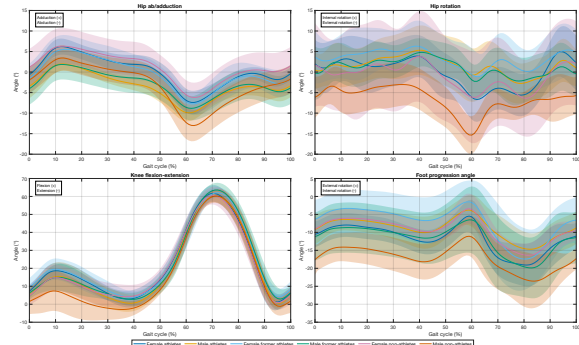


Figure 2 Joint angles of the different categories along the gait cycle

To support the obtained results, the GDI, GPS, and the corresponding GVS were evaluated. In non-athletic males, the GDI showed a median of 88.35 and a moderate variability (IQR=9.73), lower than male athletes (106.9;  $p < 0.0001$ ) and male former athletes (99.64;  $p < 0.016$ ). The GPS was also higher ( $7.36^\circ$ ) than that of athletes ( $4.65^\circ$ ) and former athletes ( $5.53^\circ$ ), with significant differences ( $p < 0.016$ ), indicating an overall more altered gait pattern. The increase in GPS in male non-athletes is mainly driven by the GVS related to foot progression, knee flexion-extension, and hip flexion-extension, all significantly higher compared to the sport-practicing categories.

Foot progression showed the most pronounced difference, with a median of  $10.92^\circ$  and an IQR of  $14.67^\circ$ , significantly higher ( $p < 0.0001$ ) than the values observed in the other groups ( $4.14^\circ$ – $6.83^\circ$ ). Knee flexion-extension (median  $7.63^\circ$ ) and hip flexion-extension (median  $10.95^\circ$ ) also exhibit significant differences ( $p < 0.0001$ ) when compared to the athletic groups. Considering the kinetic analysis, the results observed in the kinematic analysis are reflected in the joint moments (Figure 3). During the loading response phase, male non-athletes showed lower absorbed power at the knee level, with an average peak of  $0.4 \text{ W/kg}$ , compared to the other categories, where values range between  $0.67 \text{ W/kg}$  (male former athletes) and  $0.87 \text{ W/kg}$  (female athletes). In the same phase of the gait cycle, male non-athletes also exhibited a peak of absorbed power of  $0.69 \text{ W/kg}$  around 15% of the cycle at the hip level, whereas the other groups showed lower absorbed power and, in the case of athletes, even generated power, with a peak of  $0.26 \text{ W/kg}$ .

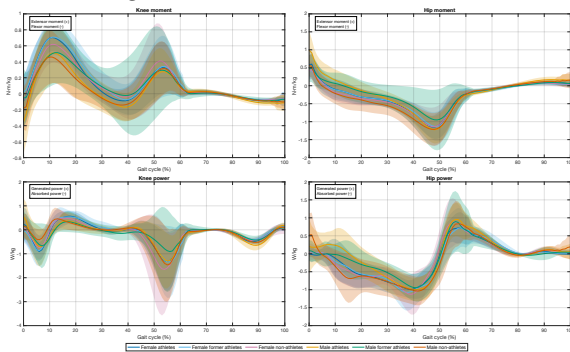


Figure 3 Joint moment and power curves of the different categories along the gait cycle

Considering gait asymmetry based on spatiotemporal parameters and calculated through symmetry indices, no statistically significant differences emerged among athletes, former athletes, and sedentary subjects. A similar result was found in the analysis of muscle activity, where the evaluation of activation frequencies did not show significant differences between the groups. From the analysis of postural stability, it emerged that in the bipodal standing test athletes showed lower median values in all temporal and frequency-domain parameters compared to former athletes and non-athletes. The same trend was observed in the eyes-closed condition, where all subjects exhibited a general worsening of the parameters due to the removal of visual input. However, no statistically significant differences were found between the categories in either

condition. The Romberg indices confirmed that the removal of visual input did not produce significant differences among the groups. Similar results were observed in the tandem standing test, where the change in the base of support led to a deterioration of both temporal and frequency-domain parameters in all categories, with slightly better values in athletes but without statistically significant differences. A difference was found in the recruitment of sensory systems when comparing the three categories collectively across the two postural tasks: in the bipodal stance with open eyes, visual contribution was higher (25–32% of total power compared to 14–21% in tandem), whereas in the tandem stance the somatosensory and open-loop contributions increased (18% vs 10% for the somatosensory component and 24–28% vs 14% for the open-loop component).

In the monopodal standing test, athletes showed significantly lower values compared to non-athletes. With eyes open (Figure 4), the median sway area was  $8.41 \text{ cm}^2$  in athletes and  $12.05 \text{ cm}^2$  in non-athletes ( $p < 0.0001$ ). Maximum excursions were also lower in athletes:  $4.14 \text{ cm}$  versus  $4.84 \text{ cm}$  in the anteroposterior direction ( $p < 0.016$ ) and  $3.10 \text{ cm}$  versus  $3.95 \text{ cm}$  in the mediolateral direction ( $p < 0.0001$ ). For the latter parameter, significant differences were also observed between former athletes and the other two categories ( $p < 0.016$ ).

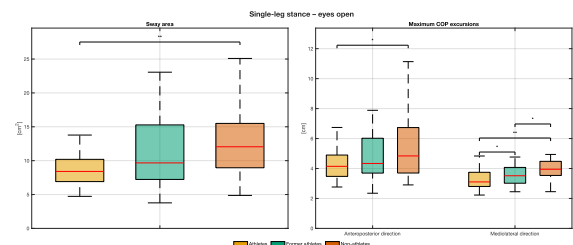


Figure 4 Temporal-domain COP parameters. Significant differences: \* ( $p < 0.016$ ) and \*\* ( $p < 0.0001$ )

Important differences emerged in the eyes-closed condition (Figure 5). Regarding the sway area, athletes showed a median of  $16.38 \text{ cm}^2$ , former athletes  $21.48 \text{ cm}^2$ , while non-athletes reached  $45.19 \text{ cm}^2$  with a very high IQR of  $96.43$ . Significant differences were found between athletes and former athletes ( $p < 0.016$ ), between athletes and non-athletes ( $p < 0.0001$ ), and also between former athletes and non-athletes ( $p < 0.0001$ ). The median of maximum excursions in the anteroposterior direction, resulted  $5.30 \text{ cm}$  in athletes,  $6.33 \text{ cm}$  in former athletes, and  $14.54 \text{ cm}$  in non-athletes. Significant differences were found among all categories: athletes vs non-athletes ( $p < 0.0001$ ),

former athletes vs non-athletes ( $p < 0.0001$ ), and athletes vs former athletes ( $p < 0.016$ ).

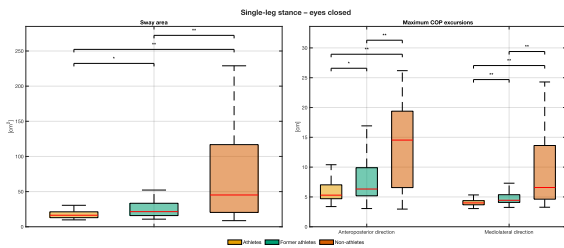


Figure 5 Temporal-domain COP parameters. Significant differences: \* ( $p < 0.016$ ) and \*\* ( $p < 0.0001$ )

In the mediolateral direction, differences were smaller but still significant: 4.00 cm in athletes, 4.44 cm in former athletes, and 6.58 cm in non-athletes, with significant differences across all groups ( $p < 0.0001$ ). In this case as well, non-athletes showed the greatest variability, with IQR values of 12.82 cm and 9.00 cm in the two directions. These eyes-closed results are reflected in the energetic demand, as shown by the total COP power in both the anteroposterior and mediolateral directions (Figure 6).

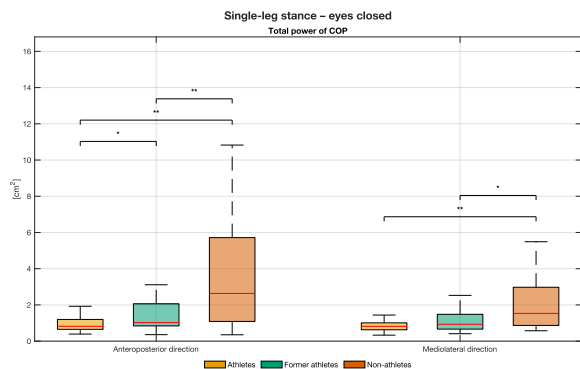


Figure 6 Frequency-domain COP parameters. Significant differences: \* ( $p < 0.016$ ) and \*\* ( $p < 0.0001$ )

In the anteroposterior direction, statistically significant differences emerged among athletes, former athletes, and non-athletes ( $p < 0.0001$ ), as well as between athletes and former athletes ( $p < 0.016$ ). The median power increases from 0.82  $\text{cm}^2/\text{s}^2$  in athletes to 1.02  $\text{cm}^2/\text{s}^2$  in former athletes, reaching 2.63  $\text{cm}^2/\text{s}^2$  in non-athletes. In the mediolateral direction, similarly significant differences were observed across the three categories ( $p < 0.0001$  and  $p < 0.016$ ), with median power values of 0.81  $\text{cm}^2/\text{s}^2$  in athletes, 0.93  $\text{cm}^2/\text{s}^2$  in former athletes, and 1.53  $\text{cm}^2/\text{s}^2$  in non-athletes. Considering the sensory contributions (Figure 7), expressed as percentage of the total power, a clear pattern emerged: all categories showed a marked reduction in visual contribution and an increase in vestibular contribution. More relevant, however,

are the strategies adopted in the use of the somatosensory system and neuromuscular control. In the anteroposterior direction, athletes made greater use of the somatosensory component compared to non-athletes (21% vs 15%,  $p < 0.0001$ ), while relying less on neuromuscular (open-loop) control (27% vs 39% in non-athletes,  $p < 0.0001$ ). Former athletes showed intermediate values, with 17% for the somatosensory component and 29% for the open-loop contribution. In the mediolateral direction, significant differences also emerged between athletes and non-athletes in the somatosensory component (21% vs 15%,  $p < 0.0001$ ), whereas the open-loop contribution remained similar across groups, ranging between 31%-34%.

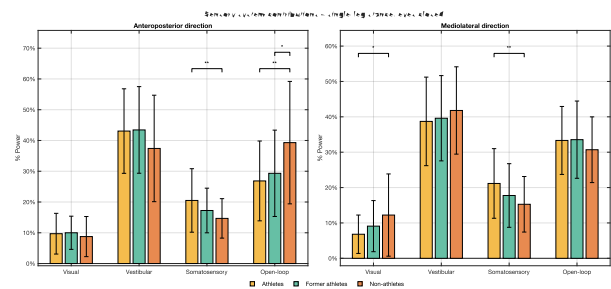


Figure 7 Sensory system contributions (%). Significant differences: \* ( $p < 0.016$ ), \*\* ( $p < 0.0001$ )

In the SLSH test, the ability to recover postural control following a jump was assessed. As shown in Figure 8, male and female athletes exhibited significantly lower values than former athletes and non-athletes ( $p < 0.008$ ) for both the sway direction and the mean COP velocity.

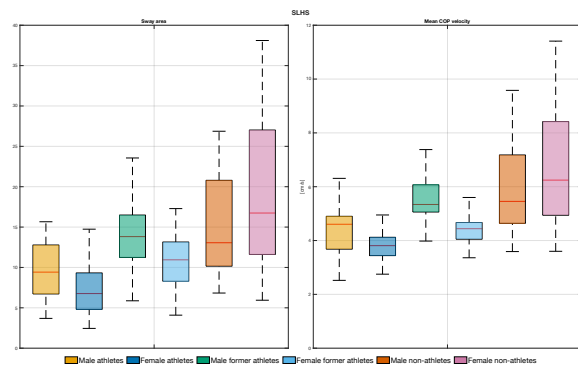


Figure 8 Temporal-domain COP parameters

Median sway areas ranged from 6.77–9.43  $\text{cm}^2$  in athletes, 10.95–13.82  $\text{cm}^2$  in former athletes, and 13.06–16.74  $\text{cm}^2$  in non-athletes. For mean COP velocity, athletes showed median values between 3.81–4.61  $\text{cm}/\text{s}$ , former athletes between 4.44–5.34  $\text{cm}/\text{s}$ , and non-athletes between 5.46–6.25  $\text{cm}/\text{s}$ . Furthermore, for these parameters no statistically significant differences were found between male former athletes and male non-athletes, whereas

very marked differences were observed between female former athlete and female non-athlete ( $p < 0.0001$ ). Finally, in the mSEBT, the values of normAP(%), normPL(%), and normPM(%) did not show marked significant differences among the groups, despite greater flexibility in athletes compared to the other categories. In the COP analysis, however, athletes displayed lower sway velocities in both posterior directions, with significant differences ( $p < 0.016$ ) compared to non-athletes.

## 5. Discussion

From the overall analysis of gait and of the kinematic and kinetic curves of the three categories examined, it appeared that sports participation may produce more pronounced benefits in male subjects than in females, both in athletes and years after sport cessation, as highlighted in particular by the different lower-limb movement pattern observed in the joint profiles of the hip, knee, and foot. Although gait quality indices support this tendency, they should be viewed as complementary rather than definitive measures, as they rely on comparisons with a control group whose sporting background is unknown. This may account for some discrepancies between the index values and the patterns observed in the kinematic curves and SPM analysis. Further research, involving a wider sample, will be necessary to more precisely assess the contribution of individual muscle groups during the gait cycle and provide a more detailed understanding of the differences observed between the categories.

Regarding postural stability, the results indicated that sports participation promotes better balance control, supported by more efficient sensory integration, enhanced muscular coordination, improved proprioception, and greater neuromuscular strength<sup>5</sup>. These adaptations, further reinforced through specific training, help to reduce the risk of instability, particularly in the presence of external perturbations, as demonstrated in the SLHS tests. In sedentary individuals, by contrast, postural control appeared less effective, particularly in the single-leg standing test<sup>6</sup>. In the absence of visual input, these subjects tended to adopt compensatory strategies involving greater trunk participation, leading to increased energy expenditure to maintain balance. Similar differences also emerged in flexibility,

where athletes showed superior performance. Finally, in former athletes, the results suggested that the positive effects of past sports participation persist even years after cessation, although to a lesser extent compared with active athletes. This is particularly evident in tasks requiring greater sensory integration and finer neuromuscular control, such as the single-leg standing test. About post-landing recovery, significant differences were observed only in female subjects. These findings indicate that sports participation induces neuromuscular and sensory adaptations that are at least partially maintained over time, although they exhibit a gradual decline when regular training is not continued.

## 6. Conclusion

In conclusion, this preliminary study showed that sports participation has a significant impact on postural stability, both in static and dynamic conditions. This effect was evident not only in individuals who currently practice sport at a competitive level, but also in those who have stopped for years: such former athletes still display postural control adaptations persisting over time, although to a lesser extent than active athletes. Regarding gait, despite the differences observed in non-athlete males compared to all other categories, further studies will be necessary to more robustly validate the evidence emerging from this preliminary analysis.

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