Lower limb muscle asymmetry measured by the method of Tensiomyography in differently trained males and females

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Abstract

The main aim of this study was to investigate differences in functional (FS) and lateral (LS) lower limb muscle asymmetry measured by tensiomyography (TMG) between differently trained participants. The sample consisted of 159 men and women divided into five groups: the physically inactive (PI), the physically active (PA), strength and power athletes (SP), endurance athletes (EA) and team sports athletes (TS). The level of muscle asymmetry was evaluated using TMG. To examine the differences between differently trained individuals and sexes in the TMG-derived parameters, two-way multivariate and univariate analyses of variance (MANOVA and ANOVA) were performed. Differences between differently trained groups ($F = 2.923$, $p = 0.004$, $\eta^2 = 0.074$) and between sexes ($F = 4.751$, $p = 0.010$, $\eta^2 = 0.061$) were found regarding the FS, where SP athletes exhibited lower values (right leg) compared to EA athletes ($p = 0.001$), and females lower values (right and left leg) than males ($p = 0.012$, on average). There were no significant differences in any other measured parameter of FS and LS. In conclusion, both physical activity type and level and sex emerged as significant independent factors that are associated to some extent with functional but not lateral lower limb asymmetry.

Keywords: muscle asymmetry; lower limb; TMG; physical activity level; sex

Introduction

Symmetry, in general, may be defined as the quality of an object to demonstrate an exact correspondence of size, shape, and form across its two halves when split along a given axis, while asymmetry presents various types of deviation from symmetry. In the human body functioning, muscle asymmetry, especially regarding lower limbs, plays an important role in everyday movement and sports activities (Pizzigalli et al., 2011; Maloney, 2019; Pajović etal, 2025; Qaduri et al., 2026). Lower limb muscle asymmetry may play a significant role in daily body functioning, recreational activities, and athletic performance (Bishop et al., 2018; Fort-Vanmeerhaeghe et al., 2021; Śliwowski et al., 2024). Such asymmetries often arise from the predominance of certain muscle groups and can manifest as disparities in strength, power, balance, flexibility, or range of motion. These differences have important implications for the training process, sport-specific performance and injury occurrence (Impellizzeri et al., 2007; Kyritsis et al., 2016; Helme et al., 2021).

Previous studies have shown that muscle asymmetry can negatively affect various aspects of sports performance, including jump height, sprinting, change of direction, movement speed, and muscular endurance (Impellizzeri et al., 2007; Jordan et al., 2015; Bishop et al., 2016; Maloney, 2019; Bishop et al., 2023). Among the lower limb muscles, the quadriceps and hamstrings have the most important anatomical and biomechanical role in the movement and stabilisation of a knee joint during these activities (Innocenti, 2022; Li et al., 2026). Lateral (inter-limb) muscle asymmetry refers to comparisons between the dominant and non-dominant, stronger and weaker, injured and non-injured limbs (Vaisman et al., 2017; Beato et al., 2021). Due to the wide range of classification approaches, there is still no universal method for quantifying the inter-limb differences, however, asymmetries are most commonly expressed as the percentage difference between limbs (Bishop et al., 2018). On the contrary, functional (intra-limb) asymmetry, particularly at the knee joint, examines the relationship between the extensor and flexor muscles within the same limb, a balance that is crucial for the effective movement execution (Bangsbo et al., 2006; Beato et al., 2021). This coordination is achieved through reciprocal activation of agonist and antagonist muscles, supported by synergistic contributions that enhance dynamic stability, protect joint structures, and facilitate efficient force transfer during complex motor actions (Latash, 2018).

Various methods and metrics are used to assess lower limb muscle asymmetry, with the most common analysis focusing on differences in muscle strength and power. The most reliable method in these assessments includes vertical jumps and isokinetic dynamometry (Baroni et al., 2020; Bishop et al., 2023). Additionally, lower limb asymmetry can be measured through differences in other means, including flexibility (Daneshjoo et al., 2013), electromyography (Kwok et al., 2023), and, more recently, tensiomyography (TMG). TMG is a non-invasive diagnostic tool that measures spatiotemporal characteristics of muscle response induced by electrical stimuli (de Paula Simola et al., 2016; Martín-Rodríguez et al., 2017; Kusumoto et al., 2023). TMG is widely used in sports practice to assess muscle fatigue, recovery and optimising training adaptations through assessment of muscle stiffness, responsiveness, contraction velocity, and others (Loturco et al., 2015; García-García et al., 2019; Yildiz et al., 2021; Toskić et al., 2022). In clinical practice, it is also employed to diagnose neuromuscular disorders (de Paula Simola et al., 2015). Lastly, TMG is a valuable measuring tool for identifying lateral and functional asymmetries in lower-limb muscles (Gil et al., 2015; Alvarez-Diaz et al., 2016; Buoite Stella et al., 2022; Paravlic et al., 2022, 2024; Pajović et al., 2025). This non-invasive nature further makes TMG particularly well suited for comparing populations with markedly different training backgrounds and physical capacities, such as physically inactive individuals and elite athletes. Because it does not require maximal voluntary contractions, it minimizes injury risk and fatigue-related bias across heterogeneous cohorts. However, the number of studies on this topic is still limited, while conclusions vary.

It should be emphasised that recent evidence directly comparing different methods for assessment of muscle asymmetry (TMG-derived and isokinetic dynamometry-derived asymmetry) indices suggests that different methods may provide complementary rather than interchangeable information (Toskić et al., 2026).

The link between muscle asymmetry, movement performance, and injury risk is a frequently represented topic. Far less is known, however, about how different sports – or varying levels of physical activity and participation influence the degree of muscle asymmetry. This information is important from several aspects. Knowing the influence of long-term involvement in certain sports activities, or inactivity, on muscle asymmetry can contribute to shaping sports performance and injury prevention guidelines. Additionally, the knowledge about the impact of different physical activity levels from the aspects of weekly frequency, load and intensity on muscle asymmetry could contribute to the clarification of the methods for training prescription in areas such as the rehabilitation process and general health.

Muscle asymmetry of athletes from different sports has been mainly investigated regarding different team sports (soccer, basketball, volleyball, futsal) (Fort-Vanmeerhaeghe et al., 2016; Parpa & Michaelides, 2022), and symmetric versus asymmetric sports (Kalata et al., 2020; Heshmati et al., 2025). Very few studies compared several different sports-related activities and groups (Dai et al., 2019; Kalata et al., 2020), while only one study examined differences between individuals of varying levels of physical activity participation (professional athletes versus recreational athletes) (Mattes et al., 2018). Finally, no study examined these differences using the TMG method, which targets different aspects of muscle asymmetry compared to other methods. In the present study, athletes were grouped primarily according to their physical activity level and the predominant physical demands of their sport (e.g., strength–power, endurance and mixed output), consistent with common classification approaches in sports science, rather than strictly by movement pattern symmetry. It is acknowledged that this approach combines athletes with markedly different biomechanical profiles, such as combat sports and cyclic power disciplines, within the strength–power category. Nevertheless, the existing evidence linking training type and physical activity level to the magnitude of lower-limb asymmetry remains scarce and inconsistent, suggesting that any such differences may be modest rather than pronounced. From a physiological and biomechanical standpoint, it has been speculated that cyclic activities such as running, cycling, and swimming, which involve repetitive bilateral loading, may be associated with lower asymmetry compared to unilateral or asymmetric sports, which can promote side-to-side differences in muscle stiffness and contraction properties (Carpes et al., 2010; Colomar et al., 2022). However, this mechanistic link has not been directly established, and the extent to which it translates into measurable differences in TMG-derived symmetry indices remains to be empirically tested.

Therefore, the main aim of this study was to investigate differences in functional and lateral lower-limb muscle asymmetry measured by TMG between differently trained men and women. Additionally, this study aims to determine the differences in muscle asymmetry according to sex. Consequently, we hypothesised that there are significant differences in lower-limb muscle asymmetry between these groups.

Material and methods

Experimental approach to the problem

A cross-sectional study design was used to assess differences in both functional and lateral asymmetries in muscle mechanical and contractile properties across participants with varying trainability. Each subject was measured once and assigned to one of five groups based on physical-activity profile: physically inactive (PI), physically active (PA), strength and power athletes (SP), endurance athletes (EA), and team-sport athletes (TS). The present study represents a secondary analysis of data collected within a broader research project on the neuromuscular characteristics of differently trained individuals (Project No. III47015, Ministry of Education, Science and Technological Development). Selected anthropometric and TMG contractile parameters of this cohort have been reported previously (Toskić et al., 2019, 2020, 2022); however, the functional and lateral asymmetry indices derived from these measurements, and their comparison across physical-activity groups and between sexes, which constitute the focus of the present study, have not been previously calculated, reported, or analysed.

Participants

The sample of participants consisted of 159 individuals (Table 1; Toskić et al., 2019, 2020, 2022). The inclusion/exclusion criteria were mainly based on a weekly involvement in physical activities. The PI group consisted of adults who did not take part in physical activity. The PA group consisted of adults who took part in physical activities 2 to 5 times per week but were not professional athletes. The group of athletes consisted of top-level athletes, that is, individuals who regularly took part in professional sports training, had had training and competitive experience for no less than 5 years, and who actively competed in national and international ranks of the sports they were participating in. The additional exclusion criteria for every participant were the presence of injury or illness.

The strength and power athletes included judokas, wrestlers, karatekas, boxers, kick-boxers, and sprinters (swimmers, cyclists, runners). The group of endurance athletes included long-distance runners, cyclists and swimmers. Athletes from the group of team sports included soccer players, basketball players, volleyball players, handball players and water polo players.

All of the participants were healthy, rested, acquainted with the goals of the research, and all participants had voluntarily agreed to participate (signed an institutionally approved informed consent document). All of the testing was done in accordance with the Declaration of Helsinki and the rules of the Ethics Committee of the Faculty of Sport and Physical Education (IRB 484-2).

[Table 1 near here]

Measurement procedure

Muscle contractile characteristics and muscle asymmetry were evaluated non-invasively using TMG. We assessed the superficial muscles around the knee joint, positioning the Biceps femoris (BF) and Semitendinosus (ST) measurements with the participant prone and the knee flexed at 5°, while recordings for the Vastus lateralis (VL), Vastus medialis (VM), and Rectus femoris (RF) were obtained with the participant supine and the knee flexed at 30°. Foam pads provided standardized support for the limb in both postures. Measurements were performed in the static and relaxed condition.

Following established protocols (Toskić et al., 2019, 2022; Paravlic et al., 2022, 2024), an isometric twitch was elicited via electrical stimulation and the resulting radial displacement of the muscle belly was captured at the skin surface by a TMG-BMC digital displacement sensor (Ljubljana, Slovenia). The sensor was oriented perpendicular to the skin above the muscle belly. Self-adhesive electrodes (5 cm diameter; Axelgaard, Aarhus, Denmark) served as cathode and anode and were placed 5 cm distal and proximal to the sensor, respectively.

Electrical pulses (1 ms duration) were delivered by the TMG-100 System stimulator (TMG-BMC d.o.o., Ljubljana, Slovenia), beginning at 20 mA. Stimulus intensity was increased in 20 mA increments until the displacement amplitude (Dm) plateaued, typically at a maximum of 110 mA. To reduce fatigue and potentiation, a 10-s rest interval separated consecutive stimuli. Detailed testing procedures have been described elsewhere (Toskić et al., 2019, 2022).

From the two highest-amplitude twitch responses, the following TMG parameters were derived: delay time (Td), defined as the interval from the electrical impulse to 10% of Dm; contraction time (Tc), the time from 10% to 90% of Dm; sustain time (Ts), the duration from 50% ascending to 50% descending of Dm; and relaxation time (Tr), from 90% to 50% of Dm.

Based on those values, the algorithm for calculating both the lateral and functional asymmetries was implemented (Equations 1 and 2).). The weighting coefficients applied in Equations correspond to the standard algorithm implemented in the TMG measurement system and used in previous TMG-based asymmetry research (García-García et al., 2019; Buoite Stella et al., 2022; Paravlic et al., 2022)

Equation 1:

$$LS = 0.1\ x\ \frac{MIN(TdR; TdL)}{MAX(TdR; TdL)} + 0.6\ x\ \frac{MIN(TcR; TcL)}{MAX(TcR; TcL)} + 0.1\ x\ \frac{MIN(TsR; TsL)}{MAX(TsR; TsL)} + 0.2\ x\ \frac{MIN(DmR; DmL)}{MAX(DmR; DmL)}\ x\ 100$$

where LS represents the lateral symmetry, MIN – the minimum, MAX – the maximum, R – right leg parameters and L – left leg parameters.

Equation 2:

$$FS = 0.1\ x\ \frac{MIN(AVERAGE(TdRF;TdVL;TdVM);TdBF)}{MAX(AVERAGE(TdRF;TdVL;TdVM);TdBF)} + 0.8\ x\ \frac{MIN(AVERAGE(TcRF;TcVL;TcVM);TcBF)}{MAX(AVERAGE(TcRF;TcVL;TcVM);TcBF)} + 0.1\ x\ \frac{MIN(AVERAGE(TrRF;TrVL;TrVM);TrBF)}{MAX(AVERAGE(TrRF;TrVL;TrVM);TrBF)}\ x\ 100$$

where FS represents a functional symmetry, MIN – the minimum, MAX – the maximum, R – right leg parameters and L – left leg parameters.

Additionally, the average values of asymmetry for all muscles regarding the knee extensor (RF, VM, VL) and flexor muscles (BF, ST) were calculated.

Statistical analysis

In statistical analysis, descriptive statistics were used in which the basic measures, mean and standard deviation (SD), were calculated. The normality of data distribution within each group was assessed using the Shapiro–Wilk test, whereas the homogeneity of variances was evaluated using Levene's test. The homogeneity of covariance matrices was examined using Box's M test. To examine the differences between differently trained individuals and between sexes in the measured parameters, two-way multivariate and univariate analyses of variance (MANOVA and ANOVA) with the factors Physical activity – PA (PI, PA, SP, EA, TS) and Sex (male and female) were performed (MANOVA – separately for functional (FS) and lateral asymmetry (LS); ANOVA – one for each observed parameter). The Bonferroni post-hoc analysis was applied for all variables that showed significant general differences between groups in variables of FS (FS R and FS L) and LS (LS RF, LS VL, LS VM, LS BF, LS ST, LS Qavg, LS Havg). To examine the differences between males and females in observed variables, a t-test was used. Effect sizes were calculated using partial eta squared (η^2) for the ANOVA, with the following classification for magnitude effects (Cohen, 1988): small effect (0.01), moderate effect (0.06) and large effect (0.14). The statistical analysis was performed using IBM SPSS Statistics software package (version 25, SPSS Inc., Chicago, IL, USA), and Microsoft Office Excel 2024 (Microsoft Corporation, Redmond, WA, USA). All variables are presented as mean and standard deviation. A significance level of $p \leq 0.05$ was considered statistically significant for all comparisons.

Results

Descriptive statistics parameters for FS and LS variables are presented in Table 2. Furthermore, the data displayed in Table 3 show the results of MANOVA, which indicate that the applied analysis revealed significant differences in the main factors of PA ($F = 2.923$, $p = 0.004$, $\eta^2 = 0.074$) and Sex ($F = 4.751$, $p = 0.010$, $\eta^2 = 0.061$) regarding FS. However, the

PA × Sex interaction in FS parameters did not reach significance ($F = 0.700$, $p = 0.692$, $\eta^2 = 0.019$), and no significant general differences were observed in LS ($F = 1.283$, $p = 0.330$, $\eta^2 = 0.059$, on average). Subsequent analysis of variance (ANOVA, Table 4, Figure 1) has shown that a difference in the PA factor was spotted in variable FS R ($F = 4.078$, $p = 0.004$, $\eta^2 = 0.100$). Regarding differently trained subjects, differences were observed between SP and EA groups in the FS R parameter ($p = 0.001$). While MANOVA did not observe significance in factor PA for LS variables, it is fair to point out that ANOVA noticed significance on variable LS VL ($F = 2.916$, $p = 0.023$, $\eta^2 = 0.074$) between differently trained subjects, and as expected, Bonferroni adjustment did not detect any differences in pairwise comparisons ($p > 0.05$), regarding the last-mentioned variable. Sex differences in analyzed TMG variables were achieved in FS R ($F = 5.606$, $p = 0.019$, $\eta^2 = 0.037$) and FS L ($F = 7.721$, $p = 0.006$, $\eta^2 = 0.050$) (Table 4, Figure 2). Bonferroni test determined that in the case of both of these FS variables, males were superior to females (FS R: $p = 0.028$; FS L: $p = 0.008$). On the other hand, it should be mentioned that LS Qavg reached significance ($F = 4.085$, $p = 0.045$, $\eta^2 = 0.027$), although MANOVA revealed no significance on LS-derived variables (Table 4).

[Table 2 near here]

[Table 3 near here]

[Table 4 near here]

[Figure 1 near here]

[Figure 2 near here]

Discussion and implications

This study investigated the differences in functional and lateral lower-limb muscle asymmetry measured by the TMG, in men and women with varying training backgrounds. To our knowledge, this is the first investigation of lower limb muscle asymmetry across distinct levels of physical activity and across multiple sport categories. Furthermore, it represents the first application of the TMG method to this research question. The findings may provide novel insights into how different levels and types of physical activity influence the manifestation of functional and lateral muscle asymmetries in the lower limbs. Such knowledge could inform the optimisation of training strategies in both professional and recreational athletes, enhance rehabilitation protocols, and ultimately contribute to improved athletic performance and reduced injury risk in sport and physical activity contexts.

The results obtained in this study revealed the general differences in the FS of lower limb muscles considering PA and Sex, without interaction of these two factors (Table 2). Further, on the general level, there were no significant differences in LS, from the aspects of physical activity level, sex or interaction of these factors (Table 2). When observing the differences between differently trained subjects in individual parameters, it can be concluded that there are significant differences in FS R (Table 3). Namely, it has been shown that strength and power athletes have lower values of FS than endurance athletes by 13.3 % ($\eta^2 = 0.100$) (Figure 2). No significant differences were observed in the other parameters between differently trained individuals (Table 3).

TMG is a measurement tool primarily used for assessing various temporal characteristics of muscle contraction (Tc, Td, Tr, Ts parameters) and muscle stiffness (Dm parameter). Lateral asymmetry represents the differences in parameters Td, Tc, Ts, and Dm between measured muscles of the right and left leg, while the functional asymmetry is defined as a difference in Td, Tc, and Tr between knee joint extensor muscles RF, VM, VL, and flexor muscle BF (García-García et al., 2015; 2019; Pajović et al., 2025). Accordingly, based on the results of this study, it can be concluded that there are significant differences between differently trained men and women in functional asymmetry of the lower limb muscles regarding temporal characteristics of muscle contraction and muscle stiffness.

These results are somewhat expected. The higher FS level of endurance athletes compared to the strength and power athletes can be explained by the lowest level of FS of the right leg in the SP group. Namely, although non-significant, the SP group also showed a lower level of FS of the right leg (71.3 % on average) than the PI (74.8% on average), PA (75.3 % on average), and TS group (75.8 % on average). This phenomenon can be explained by the structure of the participants in this group and specific movement patterns in which these athletes are mostly engaged. The SP group is mainly composed of athletes from combat sports (judo, wrestling, karate), which are dominantly asymmetric physical activities. On the other hand, the EA group is composed of athletes from cyclic types of sports such as running, swimming and cycling, and this group showed the highest level of both FS and LS (80.6 %, on average). One plausible explanation is that endurance sports involve highly repetitive bilateral movement cycles that expose both lower limbs to comparable mechanical loading over prolonged periods (Kalata et al., 2020; Heshmati et al., 2025). In contrast, many strength and power sports represented in the present sample (especially combat sports) may involve preferred unilateral stance techniques and repeated asymmetric loading. Over time, these sport-specific movement characteristics may contribute to different patterns of neuromuscular adaptation and consequently different levels of TMG-derived muscle symmetry. However, because the SP group comprised athletes from several disciplines with different movement characteristics, this interpretation should be considered speculative and requires confirmation in more homogeneous athletic populations.

Although some previous studies indicated the lack of differences in muscle asymmetry between athletes from different sports (Dai et al., 2019), it could be assumed that there are significant differences between differently trained individuals, especially regarding the level of physical activity; physically inactive vs. physically active non-athletes vs. professional athletes. However, as previously stated, there were no significant differences between groups in any observed parameter. This result may also be influenced by the structure of participants and the type of physical activity implementation in these groups, rather than the amount of physical activity per se. Namely, TS athletes participate in physical activities which contain both cyclic (running, swimming) and acyclic activities (kicking, shooting, dribbling, etc.). However, the lack of differences between the groups of athletes (SP, EA, TS) and the groups of non-athletes (PI and PA) is intriguing and may be explained by the high level of both FS and LS in all groups. The cutoff values for FS and LS are 65 % and 80 %, respectively (García-García et al., 2019; Buoite Stella et al., 2022; Paravlic et al., 2022), and participants from all groups showed a sufficient level, on average (FS = 75.5 %, LS = 82.9 %). Although the PI group expressed the lowest values of FS and LS (78.3 %, on average), it may be inferred that, within the present sample, lower levels of physical activity were not associated with greater TMG-derived knee joint muscle asymmetry. The absence of significant differences between moderately active individuals (PA) and professional athletes (SP, EA, TS) may be explained by differences in training structure, load, and frequency across these groups. Recreational participants are typically motivated by general health and physical fitness (Molanorouzi et al., 2015), and their training is often carefully dosed to achieve and maintain a high level of muscular function. In contrast, the primary objective of professional athletes is competitive performance and sporting success. Their training regimens and daily routines may prioritise performance outcomes over overall health, which could contribute to levels of muscle asymmetry comparable to those seen in moderately active or even inactive individuals.

The second aim of the study was to investigate the differences in muscle asymmetry between sexes. The results revealed significant differences between sexes in parameters FS R, and FS L, where females had lower values of functional asymmetry (5.9 %, on average) than males. These differences emerged across the entire sample, regardless of training status. The findings suggest that sex may influence, to some extent, TMG-derived functional muscle asymmetry of the knee musculature. However, based on the small to moderate effect size (0.043, on average), these results should be interpreted with caution. This result is consistent with earlier studies (Ford et al., 2003; Pappas & Carpes, 2012; Bailey et al., 2015; Lisee et al., 2019), and highlights the need for extra care when designing training programs for females.

From a practical perspective, although the observed differences were relatively small, practitioners may consider monitoring muscle asymmetry in strength and power athletes and female athletes as part of a broader neuromuscular assessment rather than relying solely on TMG-derived measures. In this context, strength and power athletes, who displayed lower right-leg functional symmetry, may benefit from unilateral and corrective training to address imbalances that may undermine performance or increase injury risk. In females, lower functional asymmetry of the knee extensors suggests that attention should be given to balancing quadriceps strength bilaterally to reduce potential injury risk. More broadly, the finding that cyclic physical activities promote muscular symmetry indicates that incorporating such activities into training or rehabilitation programmes may help both athletes and the general population support joint health, maintain balanced muscle function, and enhance long-term performance and resilience.

The most significant limitation of the present study is the method used for the assessment of muscle asymmetry. Because TMG assess, defines and quantifies asymmetry differently from other methods (unvoluntary static contractions, different calculation algorithm, etc.), our conclusions are limited to functional and lateral imbalances in TMG-derived variables only. Furthermore, although the sample included participants with different physical activity types and levels, the study may not have been sufficiently sensitive to detect small between-group differences. Also, some groups are unequal regarding age (ES group), which could also affect the muscle asymmetry results (Lyu et al., 2025; Paravlic, 2025; Sha & Dai, 2025). Additionally, limb dominance was not recorded. As dominance may influence inter-limb asymmetry measures (Fernández-Baeza et al., 2024; 2025), future studies should consider accounting for dominant and non-dominant limbs when interpreting TMG-derived lateral asymmetry. The menstrual cycle phase of female participants was also not standardised or recorded. As hormonal fluctuations may influence neuromuscular characteristics (Weidauer et al., 2020), future studies should consider controlling for menstrual cycle phase when examining TMG-derived muscle asymmetry. Finally, we did not control for athletes' training and competition seasons, and these seasonal factors could have affected the results.

Conclusion

In conclusion, participants engaged in cyclic physical activities exhibited higher levels of muscle symmetry regarding the temporal characteristics of muscle contraction and muscle stiffness. Furthermore, both physical activity type and level and sex emerged as significant independent factors that are associated to some extent with functional but not lateral asymmetry. As the first TMG study to investigate these relationships across a broad population with varying physical activity types and levels, these findings provide valuable insights into muscle asymmetry and may inform future research and applications in performance enhancement and injury prevention.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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