From strength to stability: muscular holding capacity characterized by Adaptive Force—relevance and implications of an alternative approach to musculoskeletal complaints and non-contact injuries

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Abstract

Background: Musculoskeletal complaints and non-contact injuries remain poorly understood. Conventionally assessed pushing strength shows limited association and predictive value. As it does not represent the muscle function at which injuries occur—holding or braking under load—novel approaches are needed. This study focuses on muscle stability assessed by Adaptive Force (AF)—the capacity to adapt to increasing external loads while maintaining a static position—and aimed to characterize stable and unstable muscles, evaluate the robustness of key parameters, and derive practical implications.

Methods: AF data from 481 stable and 307 unstable trials of 112 muscles (elbow/hip flexors, pectoralis major) from six studies were synthesized and re-evaluated, supplemented by single cases. AF was assessed using objectified manual muscle testing in both states (stable/unstable) with identical muscles; conditions were elicited by various interventions. AF parameters (e.g., AF_{max}: peak AF; $AFiso_{max}$: max. isometric AF and their ratio) were compared using paired t-tests and mixed ANOVA with factors muscle, tester, participant sex, and experiment.

Results: Unstable muscles showed significantly reduced $AFiso_{max}$ but higher AF_{max}. AF-Ratio averaged ~56% in unstable and ~99% in stable state (d = 2.7). While absolute parameters were influenced by the tester—likely confounded by the non-balanced tester-participant constellation—relative AF parameters were robust to all factors. Unstable muscles are not weak: they fail to access their full force capacity isometrically but generate it only during lengthening.

Conclusion: Shared neural substrates for motor control, somatosensation, and emotion provide a plausible neuroanatomical basis for the observed immediate and reversible switching between stability and instability. The concept of functional instability syndrome (FIS) is proposed: muscle instability likely destabilizes joints, representing a potential key factor in the development of complaints and injuries. The AF-Ratio is self-referenced and sensitive, suggesting broad applicability for screening, prevention, diagnostics, and individualized therapy derivation. Further studies are required for validation.

1 Introduction

Musculoskeletal complaints and non-contact injuries remain among the most prevalent health issues in both athletic and general populations, yet their causal mechanisms are insufficiently understood. Non-contact injuries typically occur during active deceleration and dynamic stabilization—when external forces must be absorbed [1–10]. Paradoxically, muscle function is almost exclusively assessed during pushing actions (maximal voluntary isometric contraction (MVIC), isokinetic testing). However, converging evidence indicates that conventionally assessed muscle strength—whether absolute values, ratios or asymmetries—does not adequately explain the occurrence of musculoskeletal complaints. Reviews have found that strength measures offer limited predictive validity for hamstring or ACL injuries [10–14], with none of 13 strength-related variables reaching significance in a meta-analysis of 78 prospective studies [12]. Notably, even well-trained athletes with no apparent strength deficits regularly develop non-contact injuries and musculoskeletal complaints—further questioning the explanatory value of conventional strength parameters. In low back pain—one of the most prevalent musculoskeletal conditions—reviews found no clear relationship between strength imbalances and complaints, inconsistent results across muscle groups with unclear causality, and no pain reduction through strength normalization [15,16]. Existing systematic reviews may further overestimate the strength–injury association due to selection bias, as some restricted inclusion to studies reporting significant associations—yet even then, the reported evidence was only moderate [17]. Collectively, these findings challenge the prevailing strength paradigm and raise the question whether the parameters typically examined capture the aspects of neuromuscular control that are functionally relevant for the development of complaints and injuries.

A critical, yet largely overlooked dimension of muscle function is the capacity to hold and adapt to external forces—rather than to produce force against a resistance. In everyday life and sport, muscles are frequently required to maintain or adjust joint positions against varying loads: during

landing, changes of direction, or walking downstairs. These tasks demand a continuous adaptation of muscle tension to match the momentarily acting external force while preserving muscle length and joint position. This holding function fundamentally differs from pushing: it requires a permanent sensorimotor feedback loop in which proprioceptive and kinesthetic information about muscle length, muscle tension, joint angle, and external load is integrated, compared with the intended motor command, and continuously adjusted [18–20]. The limiting factor is therefore not maximal strength but the quality of sensorimotor control.

Recent research supports this distinction of holding (HIMA) and pushing isometric muscle actions (PIMA) which can be differentiated by objective parameters, with HIMA requiring more complex sensorimotor control [21–23]. However, most studies on HIMA have used constant loads. Adapting to variable, especially increasing external forces—as required in most functional activities—challenges the neuromuscular system even further.

The term muscle stability was introduced to describe this specific neuromuscular capacity: the ability of a muscle to maintain its length (isometric condition) while adapting to external forces. Unlike pushing strength, this capacity reflects the functional demands of everyday and sport activities more closely. If this capacity is compromised, joints may not be adequately stabilized, rendering the structures more vulnerable to strain—even under habitual loads. Muscle stability is thus the functional foundation upon which joint stability depends.

To quantify muscle stability, the concept of Adaptive Force (AF) was introduced [24,25] and further developed using both pneumatic measurement systems [26–29] and objectified manual muscle testing [30–36]. AF refers to the neuromuscular capacity to adapt to increasing external loads while maintaining a static position; thus, it is based on HIMA. The maximal force achieved under isometric conditions ($AFiso_{max}$) reflects the holding capacity. If $AFiso_{max}$ approximates the peak force (AF_{max}), the muscle is considered stable. If, however, the muscle begins to lengthen at submaximal intensities—yielding before reaching its force capacity—the muscle is classified as unstable; $AFiso_{max}$ is then substantially lower than AF_{max}. Crucially, this does not reflect a strength

deficit: the peak force during the subsequent eccentric phase mostly equals or exceeds that under stable conditions or the MVIC. The muscle is not weak; it is unstable.

Previous studies have demonstrated that the holding capacity reacts with high sensitivity and immediacy to various stimuli. Disruptive inputs—such as negative emotional stimuli or proprioceptive irritation—led to an immediate and substantial reduction of $AFiso_{max}$ (−44%) in healthy individuals [31–35]. Long COVID patients similarly showed markedly reduced muscle stability (−53%) in their disease state [36,37]. Conversely, supportive inputs—including positive emotional stimuli, proprioceptive re-adjustment, and targeted treatment—restored stability immediately [31–37]. Thus, muscles can switch instantaneously between stable and unstable states, strongly suggesting a reflexive mechanism. The neurophysiological pathways through which such diverse stimuli may affect motor control will be addressed in the Discussion.

The present study synthesizes and re-evaluates the available AF data from six previously published studies [31–36] by pooling 481 stable and 307 unstable trials from 112 muscles of 71 participants—with each muscle measured in both states within the same individual. The aims are to (1) characterize the fundamental differences between stable and unstable muscles based on AF parameters and (2) evaluate whether the key parameters are robust across potentially confounding factors. Illustrative single cases complement the analysis to demonstrate and discuss practical relevance. The underlying hypothesis is that shifting the perspective from strength to muscle stability may provide a more adequate framework for understanding musculoskeletal complaints and non-contact injuries.

2 Materials and methods

All available AF data from six studies with healthy participants [31–35] and long COVID patients [36] were merged and analyzed for the present study, complemented by illustrative single cases. AF was compared for identical muscles between their stable and unstable state. All measurements were performed at the Neuromechanics Laboratory of the University of Potsdam using an

objectified manual muscle test (MMT) executed by two experienced testers (tester A: male, ~64 yrs., 185 cm, 87 kg, MMT experience: ~27 yrs.; tester B: female, ~35 yrs., 168 cm, 55 kg, MMT experience: ~8 yrs.).

2.1 Participants

A total of 112 muscles from 71 participants (31 m, 40 f; age: 34 ± 13 yrs., range: 19–70; body mass: 71.8 ± 12.4 kg, body height: 174.5 ± 10.0 cm) were included in the present evaluation. Fifty-four participants were healthy (i.e., asymptomatic; 28 m, 26 f; 30 ± 11 yrs., range: 19–70) and participated in the experiments designed to provoke instability or stability through emotional imagery [33,34], odor perception [35], or muscle spindle conditioning [31,32]. The remaining 17 participants had the medical diagnosis long COVID (3 m, 14 f; 45 ± 14 yrs., range: 21–63), in whom AF was measured in the disease state and after recovery [36]. Four additional participants (2 m, 2 f) served as illustrative single cases in specific contexts. They were not included in the inferential statistics to preserve the systematic character of the group analysis.

Inclusion criterion for the statistical analyses was the availability of clear stable and unstable trials for at least one muscle per participant. Classification into stable and unstable trials was based on the clinical assessment of the experienced testers during the respective studies (see procedure). This classification showed excellent agreement with the objective data, with 98% of all trials being confirmed by the AF-Ratio ($AFiso_{max}/AF_{max}$) above and below 0.90 for stable and unstable muscles, respectively (see Results). In total, 56 elbow flexors, 53 hip flexors and 3 pectoralis major muscles were considered for evaluation.

The studies on which this article is based were conducted according to the guidelines of the Declaration of Helsinki and were approved by the Ethics Committee of the University of Potsdam, Germany (protocol code 35/2018). All participants gave their written informed consent to participate.

2.2 Technical equipment

The MMTs were objectified by a wireless handheld device that simultaneously records reaction force and limb kinematics during the test, thereby providing continuous quantitative data rather than a subjective grading. The device contains strain gauges (co. Sourcing map, model: a14071900ux0076, precision: 1.0 ± 0.1%, sensitivity: 0.3 mV/V) and kinematic sensors (Bosch BNO055, 9-axis absolute orientation sensor, sensitivity: ± 1%) at a sampling rate of 180 Hz. Data were AD-converted and transmitted via Bluetooth to a tablet (Sticky notes, comp.: StatConsult, Magdeburg, Germany). The force profiles of this instrumented MMT have been shown to be reproducible [30].

2.3 Manual muscle tests and settings

AF was assessed during objectified standardized MMTs performed as break tests [31–36]. The tester applied a standardized increasing force on the participant's limb by pushing against it in the direction of muscle lengthening, while the participant was instructed to maintain the starting position (HIMA). Hence, they had to adapt to the increasing force in a static position. In addition to the objective data, the tester rated each trial as 'stable' (position maintained throughout the force increase—reflecting adequate adaptation) or 'unstable' (limb yielding at submaximal intensities—inadequate adaptation). During the eccentric phase of unstable trials, force typically continued to increase until peak force was reached.

All MMTs were performed in the supine position. Joint angles were standardized at 90° for elbow and hip flexor tests. For pectoralis, the shoulder was positioned in 90° forward flexion with full elbow extension and maximal internal rotation. The handheld device was applied at the distal forearm or thigh, with contact points marked for intra-individual standardization across trials. For details of settings and procedures see [31–36].

2.4 Procedure

Although the AF assessment was identical across the six studies included, the experiments designed to provoke muscle instability or stability differed: two studies compared pleasant vs. unpleasant food imagery [33,34], one investigated pleasant vs. unpleasant odors [35], two provoked a muscle spindle slack vs. physiological adjustment [31,32], and one measured AF in long COVID patients across disease state, treatment, and recovery [36]. In all studies two to three trials were performed per muscle and condition. Three studies of healthy participants [31,33,35] included additional baseline measurements. For the present analysis, only trials with a clear clinical rating of 'stable' or 'unstable' were included, regardless of the experimental condition. In 23 trials (~3%), the observed muscle state did not match the original hypothesis (6 stable despite hypothesized instability, 17 vice versa); these were classified according to the observed state for the statistical evaluation.

A total of 481 stable trials (238 elbow flexors, 232 hip flexors, 11 pectoralis) and 307 unstable trials (150 elbow flexors, 148 hip flexors, 9 pectoralis) were included in the present analyses. The tests of all stable and all unstable muscles were combined across muscle groups, as the evaluation is based on relative within-muscle comparisons. Post-hoc analyses evaluated, among other factors, the differences between muscle groups.

2.5 Data processing

The data were processed in the underlying studies; the corresponding values were used for the present analysis. Processing was performed using NI DIAdem 2017 (National Instruments, Austin, TX, USA) based on force and gyrometer signals (for details see [31–36]). The following parameters were extracted (Fig 1):

- AF_{max} (N): peak force of the entire trial, reached either under isometric or eccentric conditions.

- $AFiso_{max}$ (N): highest force value under isometric conditions, determined by the last zero crossing of the gyrometer signal before continuous limb movement (break point) indicating yielding. The corresponding force value refers to $AFiso_{max}$. If the isometric position was maintained throughout: $AFiso_{max} = AF_{max}$.
- AFosc (N): force at the onset of clear mechanical oscillations in force signal (≥ 4 consecutive maxima with dx < 0.15 s). Without such an oscillatory onset: $AFosc = AF_{max}$.

A conversion to torque was not performed, as only within-muscle comparisons were made (identical lever arm). The ratios $\frac{AFiso_{max}}{AF_{max}}$ (AF-Ratio) and $\frac{AFosc}{AFiso_{max}}$ were computed. The latter indicates whether oscillations arose before (< 1) or after (> 1) a potential break point. The slope of force rise was controlled in the underlying studies and did not differ between stable and unstable

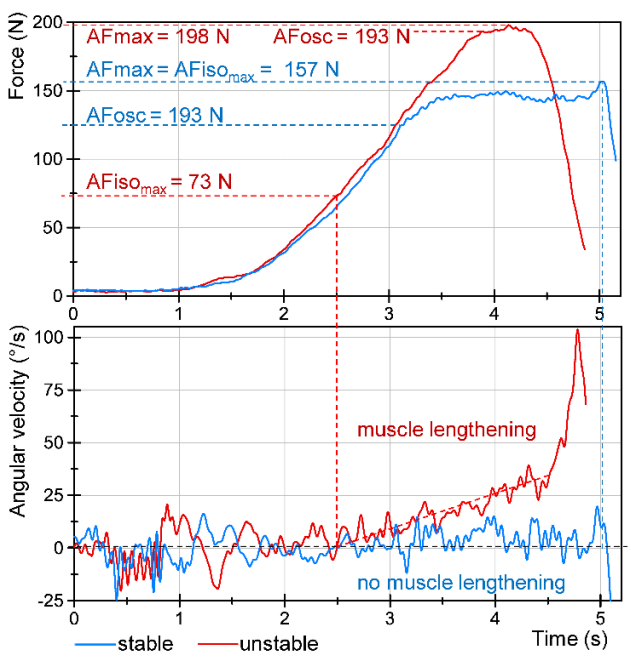

Fig 1. Exemplary stable vs. unstable AF trial of the same muscle.
Displayed are the signals of force (above) and angular velocity (gyro; below) of two AF-trials of elbow flexors of one healthy female participant (24 yrs.) during food imagery tested by the female tester. For pleasant imagery, the muscle maintained quasi-static position throughout (stable, blue), with $AFiso_{max} = AF_{max}$. In contrast, for unpleasant imagery the muscle began to lengthen at a clearly submaximal force level (unstable, red), yet reached a high peak force during the eccentric phase, with $AFiso_{max}$ substantially lower than AF_{max}. In the stable trial, oscillations in the force signal arose at submaximal level; for the unstable trial, oscillations remained absent until near the peak force. The slopes of force increase were nearly identical for both stable and unstable MMTs, mirroring the standardized force application. Marked are the values of max. Adaptive Force (AF_{max}), max. isometric AF ($AFiso_{max}$) and AF at onset of oscillations (AFosc) (all in N). Signals were filtered (Butterworth, low-pass, cut-off: 20 Hz, filter degree 5).

states, ensuring comparable force increase across conditions as prerequisite for the comparison of the AF parameters.

2.6 Statistical analysis

Arithmetic means (M), standard deviations (SD), coefficient of variation (CV), and 95%-confidence intervals (CI) were calculated for all AF parameters per muscle state (stable/unstable), muscle, and participant.

Statistical analyses were performed with SPSS Statistics 28 (IBM Corp., Armonk, NY, USA). Paired t-tests were conducted for all parameters (AF_{max}, $AFiso_{max}$, AFosc, AF-Ratio and $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$) to compare stable and unstable trials. Additionally, a mixed-model ANOVA was performed with muscle state ('stability': stable vs. unstable) as within-subject factor and the following between-subject factors: 'muscle' (elbow flexor, hip flexor, pectoralis), 'tester' (A, B), 'experiment' (imagery, odors, spindle procedure, spindle manipulation, Long COVID), and participants' sex (female, male).

Normality of difference scores (Kolmogorov-Smirnov test) was fulfilled for all parameters except $AFiso_{max}$ ($p = 0.038$) and $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$ ($p < 0.001$). However, with $n > 30$, violations of normality are considered acceptable [38]. Slight outliers (> 1.5-fold and < 3-fold interquartile range) were retained. For mixed ANOVA, Mauchly's test of sphericity was non-significant for all parameters. Since variance homogeneity (Levene's test) was not fulfilled for $AFiso_{max}$ and AFosc, main effects should not be interpreted, but post-hoc comparisons remain valid [39]. Where significant within-subject interactions were found, Welch-ANOVA was performed as simple main effect analysis to evaluate group differences within each level of muscle state. Separate repeated measures ANOVAs (RM ANOVA) were conducted within each level of significant between-subject factors (e.g., within each tester, within each sex) to confirm that the main finding held across subgroups. For between-subject factors with more than two levels, Tukey post-hoc tests were used; for factors with two levels, Bonferroni-corrected pairwise comparisons from the mixed ANOVA were reported.

Effect sizes were reported as η^2 (small: 0.01–0.059, moderate: 0.06–0.139, large: ≥ 0.14) and Cohen's d (small: 0.2–0.49, moderate: 0.5–0.79, large: 0.80–1.29, very large: ≥ 1.3) [40]. Significance level was $\alpha = 0.05$.

3 Results

3.1 General consideration of AF parameters comparing stable vs. unstable muscles

Table 1 displays the data of all parameters comparing stable vs. unstable muscles, including the results of paired t-tests. Fig 2 additionally illustrates the respective 95% confidence intervals. $AFiso_{max}$ was clearly and significantly lower for unstable vs. stable muscles with a very large effect (d = 1.9). AF_{max} was significantly higher for unstable vs. stable and showed the lowest effect (d = 0.4; ratio of AF_{max} unstable to AF_{max} stable per muscle: 1.076 ± 0.202; range: 0.435–1.860). Notably, AF_{max} was reached during muscle lengthening for unstable muscles and under static conditions for stable muscles. This is reflected by the AF-Ratio, which showed the highest effect size (d = 2.7). This clear difference is visible in Fig 2D. $AFiso_{max}$ averaged 55.8 ± 16 % of AF_{max} for unstable muscles and 99.4 ± 1.8 % for stable ones. Thus, in the unstable state—in contrast to the stable one—the static position could not be maintained up to the maximum force capacity during adaptation to the external force increase, yet comparable or even higher peak forces were

Table 1. Parameters of Adaptive Force in stable vs. unstable muscles.

Parameter	muscle state	M	SD	range	t value	*p*	*d*
$AFiso_{max}$ (N)	stable	215.36	64.78	91.7 – 377.5	20.031	< 0.001	1.893
	unstable	131.76	62.82	20.6 – 286.8			
AF_{max} (N)	stable	216.77	65.44	91.7 – 377.5	−4.344	< 0.001	0.410
	unstable	230.47	72.86	61.4 – 441.1			
AFosc (N)	stable	165.61	62.74	52.1 – 302.1	−13.991	< 0.001	1.322
	unstable	209.12	66.77	60.8 – 358.0			
AF-Ratio	stable	0.994	0.018	0.85 – 1.00	28.747	< 0.001	2.716
	unstable	0.558	0.160	0.10 – 0.91			
ratio $AFosc/AFiso_{max}$	stable	0.756	0.111	0.46 – 0.96	−11.922	< 0.001	1.127
	unstable	2.005	1.095	0.79 – 7.84			

Arithmetic means (M), standard deviations (SD) and range of AF parameters for stable vs. unstable muscles (n = 112). Results of paired t-test are given (t value, significance *p*, Cohen's *d*).
AF_{max} = peak Adaptive Force; $AFiso_{max}$ = max. isometric AF, AFosc = AF at onset of oscillations.

generated during the subsequent eccentric phase. The ratios AF_{max} unstable/stable and AF-Ratio unstable were uncorrelated ($r = -0.05$).

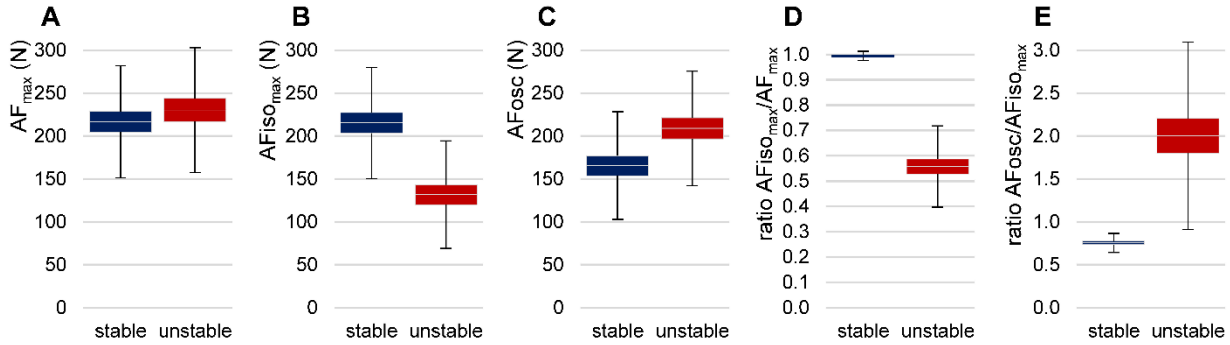

Fig 2. Comparison of AF parameters between stable and unstable state.
95%-confidence intervals including arithmetic means and standard deviations (error bars) of AF parameters (in N) and their ratios (relative values) for stable (blue) and unstable (red) muscles:
(**A**) peak Adaptive Force (AF_{max}), (**B**) max. isometric AF ($AFiso_{max}$), (**C**) AF at onset of oscillations (AFosc), (**D**) AF-Ratio, and (**E**) ratio $AFosc/AFiso_{max}$.

Categorizing the results of the AF-Ratio of all single trials in predefined percentage ranges (Fig 3), 96% of all stable trials (464 of 481) showed values between 0.95 and 1, while only 0.4% (2 of 481) were below 0.8. For unstable trials the pattern was reversed: 90% (275 of 307) showed AF-Ratio < 0.8 and 1.3% of all trials (4 of 307) were higher than 0.95. Only 1 of 307 unstable trials (0.3%) showed a ratio of 1, hence, $AFiso_{max}$ was identical to AF_{max}. For stable trials this was the case in 94% of all trials (450 of 481).

AFosc could be determined in 479 of 481 stable and 306 of 307 unstable trials. AFosc was significantly higher for unstable vs. stable muscles ($d = 1.32$). For stable muscles, the ratio $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}} < 1$ indicated that the onset of oscillations occurred before reaching AFisomax in 469 of 479 trials (98%) (Table 1, Fig 2E). Five of 479 trials (1%) had values of 1 and further five trials > 1 (average: 1.06). For unstable muscles, the oscillatory onset appeared after the break point in 280 of 306 trials (91.5%); of these, 88 trials (29% of all unstable trials) showed no oscillatory onset at all (AFosc = AF_{max}). In the remaining 26 of 306 unstable trials (8.5%), oscillations arose prior to $AFiso_{max}$ (averaged $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}} = 0.85$).

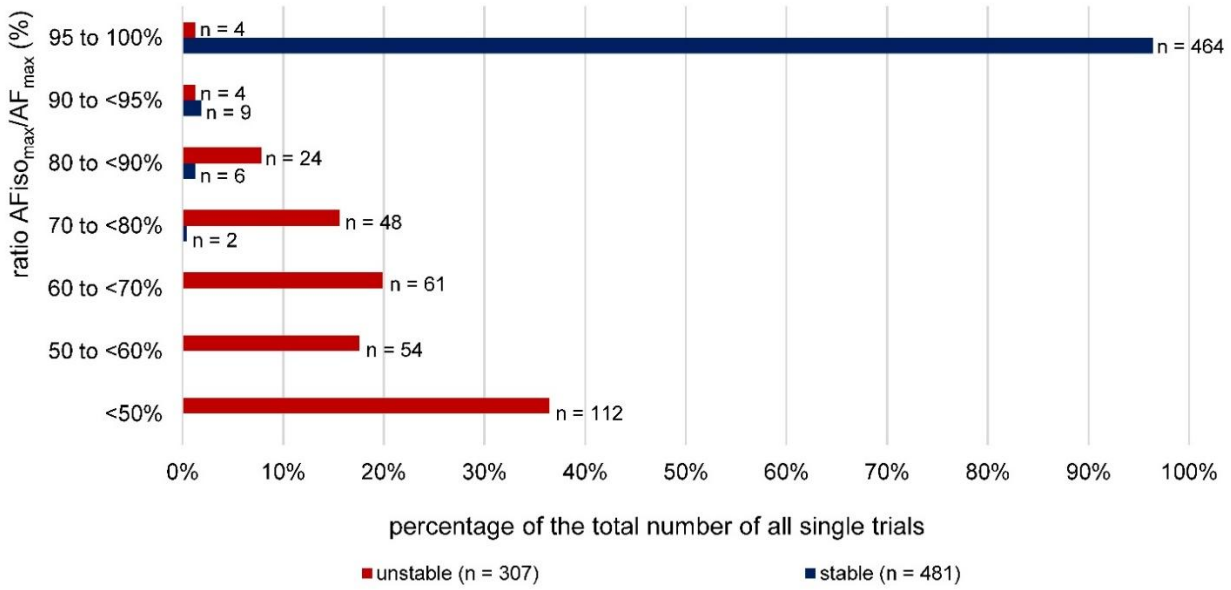

Fig 3. Distribution of the AF-Ratio across stable and unstable single trials.
Number of single trials of the relative holding capacity (AF-Ratio) categorized in percentage ranges for stable (n = 481) and unstable (n = 307) muscles.

3.2 Comparison of AF parameters regarding potential confounding factors

Fig 4 illustrates the AF results separated by factors. The mixed-model ANOVA revealed a clear significant main effect for 'stability' (stable vs. unstable) on all AF parameters. Among interpretable within-subject interactions (note: $AFiso_{max}$ and AFosc should not be interpreted due to variance heterogeneity), only the tester significantly affected AF_{max} ($F(1, 89) = 4.631$, $p = 0.034$, $\eta^2 = 0.049$). Importantly, no factor had a significant effect on AF-Ratio or $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$. A significant three-way interaction emerged for AF_{max} (stability × sex × experiment: $F(2, 89) = 3.750$, $p = 0.027$, $\eta^2 = 0.078$); all other factor interactions and multiple factor comparisons were non-significant ($p > 0.05$).

3.2.1 Differences regarding assessed muscles

None of the AF parameters showed a significant within-subject interaction for stability × muscle (Table 2, Fig 4A). The AF-Ratio showed similar patterns especially for elbow and hip flexors in stable and unstable state, respectively (Fig 5). Notably, the holding capacity dropped below 50% in 13 of 53 hip flexors (25%) and 22 of 56 elbow flexors (39%). This applied to 112 of 306 single

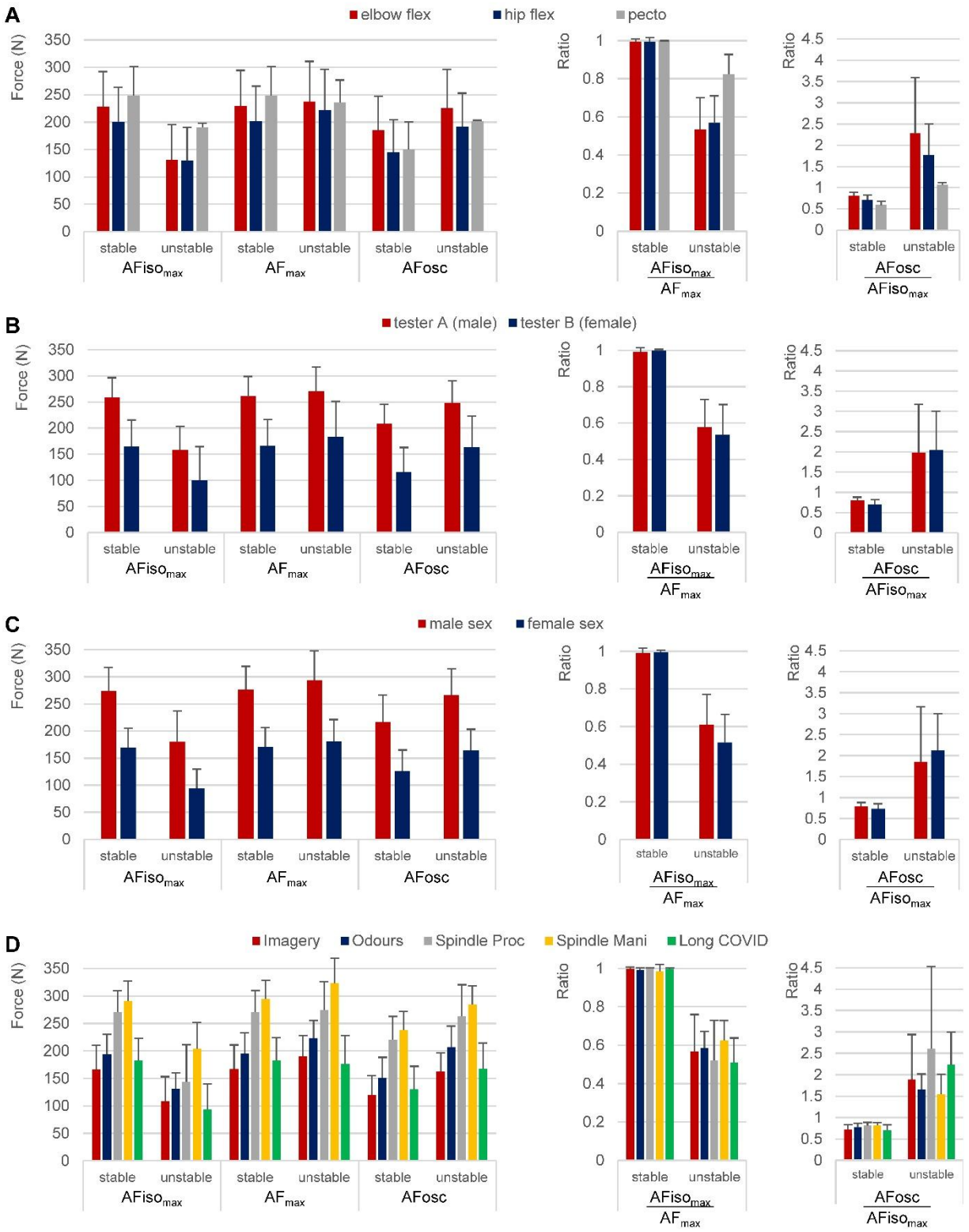

Fig 4. **AF parameters separated by potential confounding factors.**
Arithmetic means and standard deviations of the parameters maximal isometric Adaptive Force ($AFiso_{max}$), peak AF (AF_{max}), AF at onset of oscillations (AFosc) (all in N), AF-Ratio and ratio $AFosc/AFiso_{max}$ regarding the factors (**A**) tested muscle, (**B**) testers, (**C**) sex of participants and (**D**) experiment. The values are categorized in stable and unstable muscles for each factor and parameter.
Flex = flexors, mani = manipulation, pecto = pectoralis muscle, proc = procedure.

trials (37%); in 36 trials (12%) it fell below 30%. The three pectoralis muscles showed comparatively high values in unstable state (Fig 5). Across all muscles, the AF-Ratio ranged from 10.3 to 91.4% in unstable vs. 85.2 to 100% in stable state (Fig 5). This clear difference in distribution is further reflected by the CVs amounting 28.7% for unstable (elbow: 31%, hip: 25%, pectoralis: 13%) vs. 1.8 % for stable muscles (elbow: 1.4%, hip: 2.2%, pectoralis: 0%).

Table 2. Within-subject effects of mixed-model ANOVA for Adaptive Force parameters.

	$AFiso_{max}$	AF_{max}	AFosc	AF-Ratio	$\frac{AFosc}{AFiso_{max}}$
stability	**<0.001 (0.590)**	**0.008 (0.075)**	**<0.001 (0.520)**	**<0.001 (0.703)**	**<0.001 (0.239)**
stability × muscle	0.125 (0.046)	0.464 (0.017)	0.171 (0.039)	0.253 (0.030)	0.954 (0.001)
stability × tester	**0.010 (0.071)**	**0.034 (0.049)**	**0.014 (0.066)**	0.659 (0.002)	0.847 (<0.001)
stability × sex	0.804 (0.001)	0.874 (<0.001)	0.204 (0.018)	0.078 (0.034)	0.496 (0.005)
stability × experiment	0.290 (0.054)	0.085 (0.087)	0.615 (0.029)	0.701 (0.024)	0.490 (0.037)

Significance *p* and effect size eta-squared (η^2; in brackets) of within-subject effects of mixed-model ANOVA. The factors considered were stability (stable vs. unstable), muscle (elbow flexors, hip flexors, pectoralis), tester (A, B), participants' sex (female, male), and experiment (imagery, odors, spindle manipulation, spindle procedure, Long COVID).

$AFiso_{max}$ = max. isometric Adaptive Force, AF_{max} = peak AF; AFosc = AF at onset of oscillations, AF-Ratio = $AFiso_{max}$/AFmax.
Bold values indicate statistical significance ($p < 0.05$).

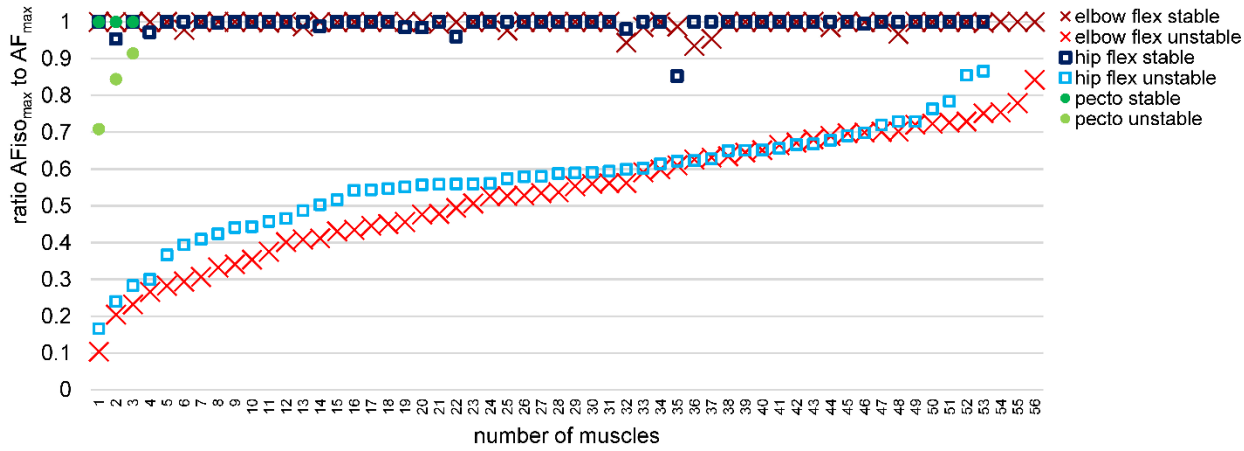

Fig 5. AF-Ratio per muscle, sorted in ascending order.
Arithmetic means of the AF-Ratio for each muscle tested (elbow flexors: red cross, hip flexors: blue square, pectoralis: green circle) and muscle state (stable: dark, unstable: light).

3.2.2 Differences regarding testers

The within-subject interaction for stability × tester was significant for $AFiso_{max}$, AF_{max} and AFosc (Table 2, Fig 4B). Welch-ANOVAs revealed a significantly lower $AFiso_{max}$, AF_{max} and AFosc for the female vs. male tester for both stable and unstable muscles (all $p < 0.001$); AF-Ratio and $\frac{\mathrm{AFosc}}{\mathrm{AFiso}_{\mathrm{max}}}$ did not differ significantly.

Between-subject effects were significant for $AFiso_{max}$ ($p = 0.048$, $\eta^2 = 0.043$), AF_{max} ($p = 0.012$, $\eta^2 = 0.068$) and AFosc ($p = 0.004$, $\eta^2 = 0.088$), not for the ratios. Pairwise comparisons showed significantly lower values for the female vs. male tester for $AFiso_{max}$ ($p = 0.001$, MD = −34.23, 95%-CI: [−54.66; −13.80]), AF_{max} ($p < 0.001$, MD = −46.38, 95%-CI: [−66.70; −26.06]) and AFosc ($p < 0.001$, MD = −48.57, 95%-CI: [−67.65; −29.49]). Comparing stable vs. unstable muscles within each tester revealed significant differences for $AFiso_{max}$ (both $p < 0.001$, $\eta^2 = 0.774$ and 0.849), AF_{max} ($p = 0.001$, $\eta^2 = 0.181$ and $p = 0.009$, $\eta^2 = 0.111$) and AFosc (both $p < 0.001$, $\eta^2 = 0.644$ and 0.643). In summary, absolute AF values differed between testers, while the relative parameters (AF-Ratio, $\frac{\mathrm{AFosc}}{\mathrm{AFiso}_{\mathrm{max}}}$) were unaffected.

3.2.3 Differences regarding sex of participants

None of the AF parameters showed a significant interaction for stability × sex (Table 2, Fig 4C). Between-subject effects were significant for $AFiso_{max}$ ($p < 0.001$, $\eta^2 = 0.215$), AF_{max} ($p < 0.001$, $\eta^2 = 0.217$) and AFosc ($p < 0.001$, $\eta^2 = 0.202$), not for AF-Ratio ($p = 0.060$, $\eta^2 = 0.039$) or $\frac{\mathrm{AFosc}}{\mathrm{AFiso}_{\mathrm{max}}}$ ($p = 0.487$, $\eta^2 = 0.005$). Post-hoc tests revealed significantly lower values for female than male participants for $AFiso_{max}$ ($p < 0.001$, MD = –69.4, 95%-CI: [–89.9; –48.9]), AF_{max} ($p < 0.001$, MD = –68.7, 95%-CI: [–89.1; –48.3]) and AFosc ($p < 0.001$, MD = –51.4, 95%-CI: [–70.5; –32.3]). The AF-Ratio was similar for stable muscles across sexes, while females showed descriptively lower values in unstable state (Fig 4C).

Comparing stable vs. unstable state within each sex confirmed significant differences for all parameters. $AFiso_{max}$ and AF-Ratio were significantly lower for unstable vs. stable muscles (all $p < 0.001$), with AF-Ratio showing the largest effect (female: MD = −0.48, $d = 3.27$; male: −0.38, $d = 2.35$), followed by $AFiso_{max}$ (female: MD = −75.7, $d = 2.02$; male: −93.74, $d = 1.87$). Conversely, AF_{max} and AFosc were significantly higher for unstable muscles, with AF_{max} showing the smallest effect (female: MD = 10.5, $d = 0.29$, $p = 0.022$; male: 17.7, $d = 0.58$, $p < 0.001$) and AFosc having large to very large effects (female: MD = 38.15, $d = 1.16$; male: 50.41, $d = 1.58$; both $p < 0.001$).

3.2.4 Differences regarding experiments

Mixed ANOVA showed no significant within-subject interaction of stability × experiment (Table 2, Fig 4D). Between-subject effects were significant for the factor ‘experiments’ regarding AF_{max} ($F(4, 89) = 3.039$, $p = 0.021$, $\eta^2 = 0.120$) and AFosc ($F(4, 89) = 2.521$, $p = 0.047$, $\eta^2 = 0.102$). Pairwise comparisons revealed significantly higher AF_{max} values for spindle procedure and spindle manipulation compared to all other experiments (imagery: $p = 0.005$ and $p < 0.001$; odors: $p = 0.041$ and $p < 0.001$; Long COVID: $p = 0.002$ and $p < 0.001$) as well as for spindle manipulation vs. procedure ($p < 0.001$). For AFosc, spindle procedure and spindle manipulation also showed significantly higher values compared to imagery (both $p < 0.001$), odors ($p = 0.017$ and $p < 0.001$) and Long COVID (both $p < 0.001$), but not between spindle manipulation vs. procedure ($p = 0.052$). Odors, imagery and Long COVID did not show any significant differences between each other.

Comparing muscle states within each experiment revealed significantly higher AF_{max} values for unstable vs. stable muscles for imagery (MD = 23.52, SEM = 6.51, $p = 0.001$, $d = 0.65$), odors (MD = 27.71, SEM = 9.75, $p = 0.019$, $d = 0.90$) and spindle manipulation (MD = 28.22, SEM = 4.73, $p < 0.001$, $d = 1.24$), not for spindle procedure (MD = 3.48, SEM = 6.33, $p = 0.590$) and Long COVID (MD = −6.37, SEM = 5.74, $p = 0.277$) (Fig 6). AFosc was significantly higher for unstable vs. stable muscles in all experiments (MD range: 37.53 to 55.97, $p \leq 0.001$, $d = 1.03$ to 2.82).

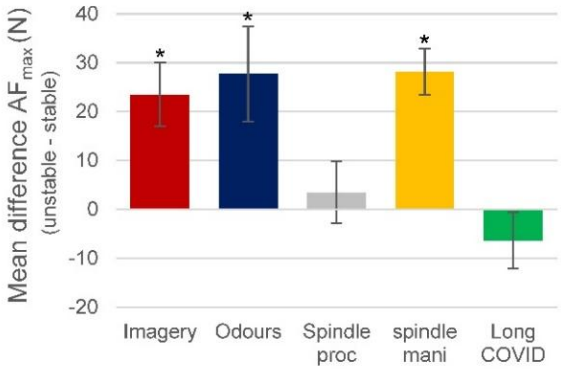

Fig 6. Differences of maximal Adaptive Force between muscle states per experiment.
Displayed are mean differences and their standard error (SEM) of the maximal Adaptive Force (AF_{max}) for each experiment. Positive values indicate higher AF_{max} for unstable vs. stable state. *$p < 0.05$.

In summary, stable vs. unstable muscles differ significantly regarding all AF parameters regardless of muscles tested, participants' sex and experiments. The tester had a significant influence on 'stability' for the absolute AF parameters only, with the female tester showing lower values than the male tester—likely confounded by the non-balanced distribution of participant sex across testers (see Discussion). Regardless of muscle state, female vs. male tester and participants showed lower values for the absolute AF parameters. Additionally, both spindle experiments showed higher values for AF_{max} and AFosc compared to the other experiments. Crucially, the AF-Ratio and $\frac{\mathrm{AFosc}}{\mathrm{AFiso}_{\mathrm{max}}}$ demonstrated no significant interaction effects.

3.3 Illustrative single cases

Further AF data were collected in the context of imagery experiments and therapeutic practice: (1) a female student under current distress (exam pressure, 27 yrs. 174 cm, 69 kg), (2) a male patient with an acute ankle inflammation (64 yrs., 187 cm, 87 kg), (3) a male patient with a subluxation of the 5th rib (65 yrs., 185 cm, 86 kg) and (4) a female participant (33 yrs, 167 cm, 56 kg) with a particularly pronounced reaction to negative food imagery. AF of elbow or hip flexors was measured analogously to the experiments described above (3 trials per state; pre- and post-intervention on the same day within ~60 min). Tester B performed measurements in Cases 1–3, tester A in Case 4. In Cases 1–3, the muscles were unstable at entry state and regained stability

after specific interventions: (1) positive imagery, (2) individualized pulsed electromagnetic field (PEMF) therapy to the ankle, (3) manual mobilization and PEMF to the rib. In Cases 2 and 3 the selection of treatment was guided by AF assessment [37]. Case 4 followed the imagery design with stable state at baseline and instability induced by negative imagery.

Fig 7 illustrates exemplary signals of AF measurements for each case. The force increase was similar across stable and unstable trials, confirming the reproducibility of force application. Mean values of all trials per case are shown in Fig 8.

In Cases 1 and 2, the pattern was consistent with the overall group: AF_{max} was at a high level for both states, while $AFiso_{max}$ was clearly reduced for unstable muscles, resulting in averaged AF-Ratios of 44% and 63%, respectively (Figs 7A, B and 8). Oscillations arose after the break point in unstable and during the isometric phase in stable trials.

In Case 3, AF_{max} was markedly lower for unstable than stable muscles (on average: ~145 vs. 233 N; Figs 7C and 8), suggesting that the nociceptive stimulus of the rib subluxation limited force generation even during muscle lengthening. After treatment, AF_{max} recovered to a high level under stable conditions (= $AFiso_{max}$). The AF-Ratio in unstable state still averaged 72% (due to the particularly low $AFiso_{max}$ of ~105 N) and 100% for stable muscles, reflecting a similar pattern to the overall group despite the low AF_{max} in unstable trials. No oscillations emerged during unstable trials, while they occurred at ~50% of AF_{max} in stable trials (Figs 7C and 8).

Case 4 showed the most pronounced reaction mirrored not only by the holding capacity ($AFiso_{max}$), but also by the peak force (Figs 7D and 8): during negative imagery, AF_{max} reached only 35% of the AF_{max} in stable condition (~68 vs. 196 N), with $AFiso_{max}$ even lower (~54 N). Although the AF-Ratio (~77%) was comparable to the overall group, it does not fully reflect the extent of the impairment in this case, as both $AFiso_{max}$ and AF_{max} were dramatically reduced. A similarly pronounced reduction of AF_{max} in the unstable state was also observed in the elbow flexor of this

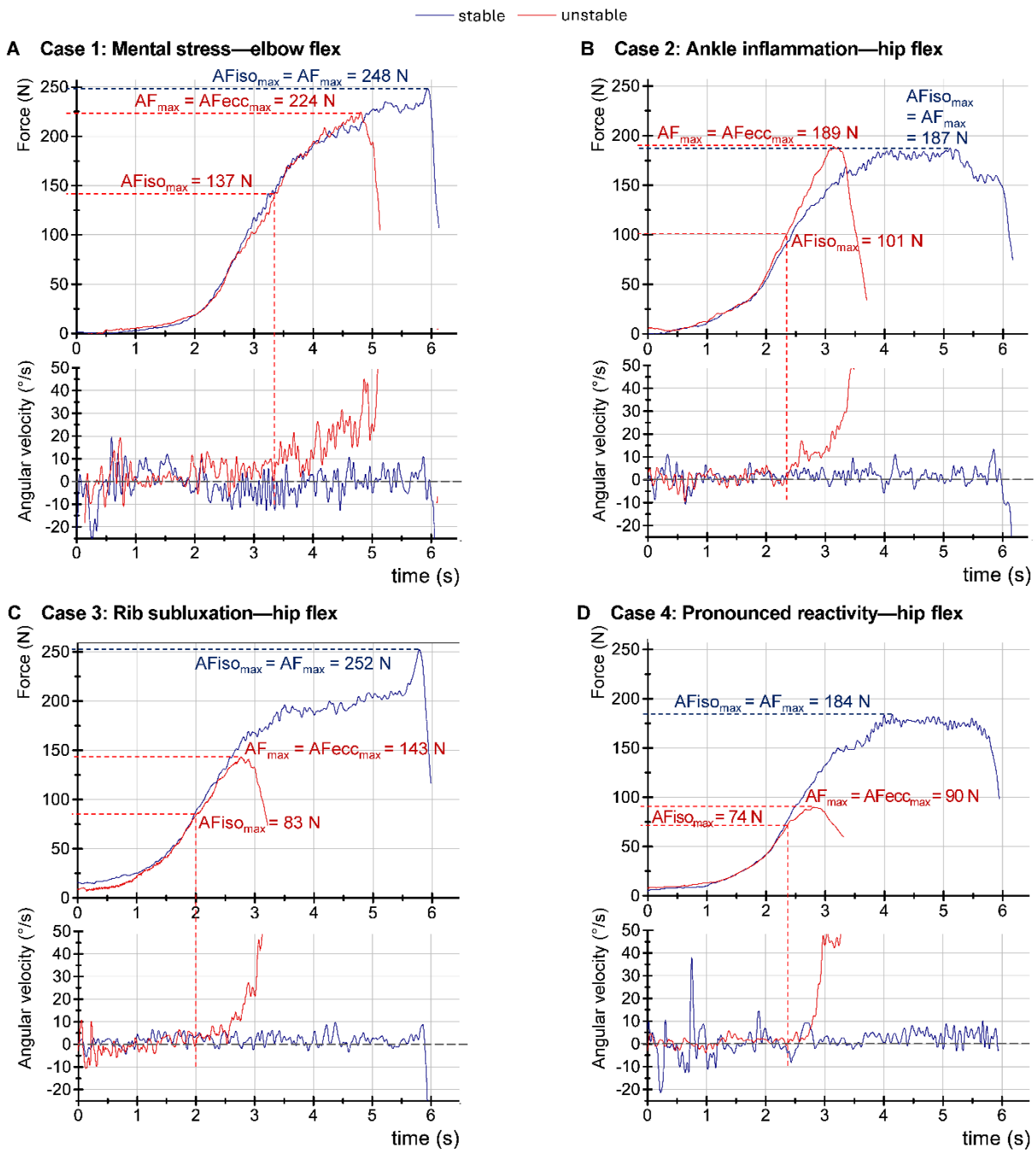

Fig 7. Single cases—exemplary signals of AF measurements.
Displayed are force (N) and angular velocity (°/s) signals of AF measurements of the identical muscle in stable (blue) and unstable (red) state.
(A) Case 1—elbow flexors of a female student with current stress (unstable) vs. positive imagery (stable).
(B) Case 2—hip flexors of a male patient with acute ankle inflammation at entry state (unstable) vs. post-treatment (stable) using pulsed electromagnetic field (PEMF) therapy.
(C) Case 3—hip flexors of a male patient with rib subluxation at entry state (unstable) vs. post-treatment (stable) using manual mobilization and PEMF.
(D) Case 4—hip flexors of a female participant during negative (unstable) vs. positive (stable) food imagery showing a particularly pronounced reaction to negative imagery.
Marked are the max. isometric Adaptive Force ($AFiso_{max}$) and peak AF (AF_{max}). In case AF_{max} was reached during muscle lengthening, the term $AFecc_{max}$ was used indicating eccentric muscle action.

364 participant (AF_{max} unstable vs. stable: ~33%; not included in Figs), indicating a generalized rather
365 than muscle-specific response.

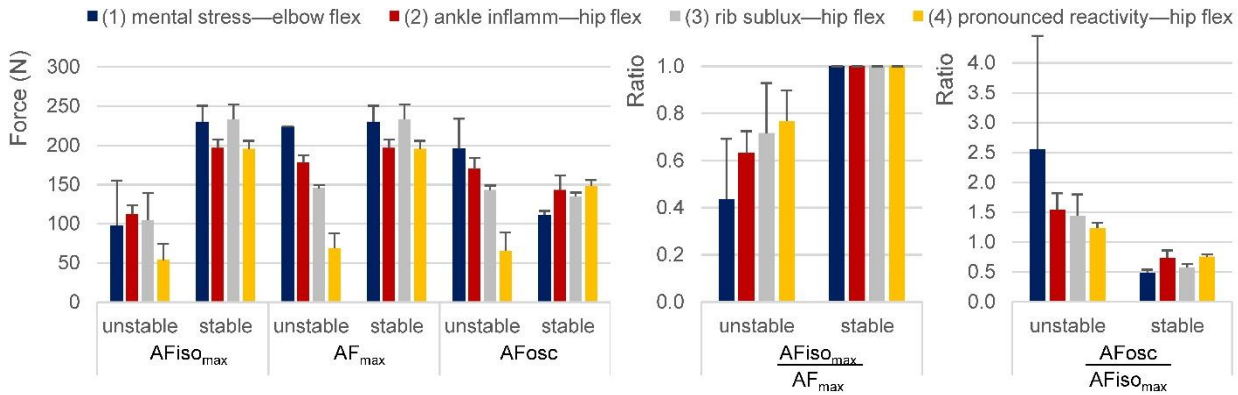

Fig 8. AF parameters of single cases.
Displayed are the arithmetic means and standard deviations (error bars) of AF parameters for the three trials per single case categorized in stable and unstable muscle state.
Case 1: mental stress (elbow flexors); Case 2: acute ankle inflammation (hip flexors); Case 3: rib subluxation (hip flexors); Case 4: pronounced reactivity to unpleasant imagery (hip flexors).
$AFiso_{max}$: max. isometric Adaptive Force (N), AF_{max}: peak AF (N), AFosc: AF at onset of oscillations (N).
366

367 # 4 Discussion

368 This study synthesized AF data from six studies comprising 788 trials of 112 muscles in 71
369 participants, with each muscle measured in both stable and unstable state. The most important
370 findings are that (1) stable and unstable muscles can be clearly distinguished by the AF
371 parameters, (2) the relative parameters—particularly the AF-Ratio—are independent of all
372 investigated factors (muscle group, tester, participant sex, experiment type), and (3) muscles can
373 switch instantaneously between stability and instability in response to various stimuli. These
374 findings on muscular adaptation are discussed below emphasizing the high potential for practical
375 implications.

376 ## 4.1 Characterization of muscle stability: stable vs. unstable

377 The findings indicate that stable and unstable muscles can be clearly distinguished. Two basic
378 key characteristics emerged:

(1) Stable muscles are able to reach their full force capacity under isometric conditions during adaptation to an increasing external load (AF-Ratio: ~99%), whereas unstable muscles yield at submaximal intensities (AF-Ratio: ~56%). Notably, unstable muscles still reach—and even slightly exceed—their peak force, but only during the subsequent eccentric phase. This suggests unstable muscles are not weak; they fail to access their full force capacity under static conditions, but retain the ability to generate high peak forces during muscle lengthening—a characterization of muscular instability. This is further supported by two of the underlying studies, which additionally assessed MVIC and revealed similar or even higher AF_{max} under both stable and unstable conditions [31,32]. Conversely, muscle stability is characterized by the ability to access full force capacity under isometric conditions. These characterizations of stable and unstable muscles likely reflect differences in the adequacy of adaptive neuromuscular control—an interpretation to be developed further in the following sections. The AF-Ratio best discriminates between the two states and—being independent of muscle group, tester, participant sex, and experiment type—appears robust across the investigated conditions.

(2) Stable muscles exhibit distinct mechanical oscillations at submaximal intensities (~75% of AF_{max}), whereas unstable muscles are characterized by markedly reduced oscillatory activity—in 29% of unstable trials, no oscillatory onset was detected at all. Previous research has demonstrated that two coupled neuromuscular systems develop synchronized oscillations during isometric interaction at submaximal intensities [41–43]. The occurrence of oscillations could be a fundamental factor in creating muscle stability in a dynamic oscillating equilibrium as during AF assessment. When an interfering stimulus is present, the development of synchronized oscillations seems to fail. Since the stimulus acts on the participant, who must adapt to the increasing force, the reduced oscillatory activity likely originates on the participant's side of the interaction. The onset of oscillations could be a sign of—or even a prerequisite for—muscular stability.

Table 3 summarizes the key characteristics of muscle stability compared to the conventional pushing strength.

Table 3. Conceptual comparison of muscle stability vs. muscle strength.

Parameter	Muscle stability	Muscle strength
Mode of action	Reactive / adaptive	Active
Assessment	Holding against external load	Pushing against resistance
Sensitivity in reaction to stimuli	High and immediate	Low
Absolute parameters from one trial	• AF_{max} = peak force • $AFiso_{max}$ = max. HIMA • AFosc = force at oscillatory onset	• F_{max} = peak force • N/A • not assessed
Ratios	e.g., AF-Ratio, AFosc/$AFiso_{max}$: describe distinct force values within one trial	e.g., H:Q ratio, LSI: describe strength balance between muscles or limbs

Key aspects characterizing muscle stability (assessed via adaptive holding muscle action) compared to pushing muscle strength, such as the maximal voluntary isometric contraction (MVIC).

$AFiso_{max}$ = max. isometric Adaptive Force; AF_{max} = peak AF; AFosc = AF at onset of oscillations; HIMA = holding isometric muscle action; H:Q = hamstrings-to-quadriceps ratio; LSI = limb symmetry index; N/A = not applicable.

4.2 Factors influencing parameters of muscle stability

A distinction must be made between factors related to the test constellation (e.g., physical conditions of tester and participants, muscle group, positioning, force application etc.) and those that affect muscle stability physiologically (i.e., disruptive or supportive stimuli). The latter are discussed in subsequent sections.

Regarding test-related factors, a few basic physical principles should be mentioned first: During manual muscle testing, the measured force is always generated by both parties simultaneously, reflecting their combined performance. The tester must adjust the applied force to the participant's capabilities and the muscle’s biomechanical requirements (e.g., less force is usually required for female participants, small muscles, or muscles tested with long lever compared to males, large muscles, or short lever tests). Consequently, absolute force values depend on the tester-participant constellation.

In the present analysis, the tester was the only factor that significantly influenced the absolute AF parameters, with the female tester showing lower values than the male tester. This could be attributed to differences in physical strength of the testers—females generally produce less

maximum force than males [44]—however, preliminary force profile testing against a fixed resistance showed that both testers achieved similar peak forces (~280 N) [30]. Another very relevant aspect to consider was the non-balanced distribution of participant sex and physical condition across testers—the male tester assessed predominantly male athletic participants in the spindle experiments—which influences the achieved peak force as well. This confounding cannot be fully disentangled with only two testers. Most importantly, the relative AF parameters were neither influenced by the tester nor by the participants' sex.

The different muscle groups showed similar patterns for stable and unstable state, indicating that the characteristics of muscle stability are consistent across different muscles. The AF assessment of additional muscle groups (knee flexors/extensors, hip flexors/adductors/abductors) in a recent study on football players (unpublished, submitted) supports this observation. The slightly higher AF-Ratio for pectoralis (n = 3) is likely related to stronger oscillations, which may have shifted the detection of the break point to higher force values. This methodological aspect should be considered in future studies with larger samples.

The factor 'experiment' significantly affected the absolute parameters AF_{max} and AFosc, with both spindle experiments showing higher values—likely attributable to the tester-participant constellation described above. Imagery, odors, and Long COVID did not differ from each other. Crucially, no experiment-related differences were found for $AFiso_{max}$ and the relative parameters, confirming that the pattern of muscle stability and instability is consistent regardless of the type of intervention used to provoke it.

Of note, only in the Long COVID group the AF_{max} was—although not significantly—on average lower in the unstable than in the stable state (Fig 6); in all other experiments, unstable muscles generated higher AF_{max} values during the eccentric phase. The absence of this pattern in Long COVID patients may indicate that in this condition, the overall force generation capacity is limited—not only the holding capacity. After treatment, muscle stability was restored immediately, with $AFiso_{max}$ returning to the level of AF_{max} [36], indicating that the limitation was reversible and

functional rather than structural. Such a pattern of markedly reduced peak force in the unstable vs. stable state—in addition to $AFiso_{max}$—is rare but clusters in identifiable subgroups. In 7 of 117 muscles (including single cases), the AF_{max} unstable/stable ratio fell below 0.7. These included two female Long COVID patients (3 muscles: 0.44–0.69), the male participant with rib subluxation (Case 3: 0.62)—in whom the affected rib was directly involved in the force transmission chain of the hip flexor test—one female participant from the imagery experiments (0.699), and the female participant showing the most dramatic reduction (Case 4; elbow flex: 0.33; hip flex: 0.35). In both of the latter, instability was triggered purely by emotional imagery, suggesting particularly high individual reactivity. Together, these observations suggest that instability may, in some individuals, extend beyond the holding capacity to also affect peak force—potentially representing a further stage of the phenomenon that can arise from severe systemic conditions, local mechanical disruption during the test, particularly high individual reactivity, or a combination of these. Importantly, the AF-Ratio itself remained within the expected range for unstable muscles even in these extreme cases, underscoring its independence from absolute force levels. At the other extreme, some individuals showed exceptionally low holding capacity (AF-Ratio < 0.4 in 18 of 117 muscles from 13 participants; see Fig 5 and single cases), reaching values as low as 10%—meaning that when external forces act on the body, stabilization fails already at clearly submaximal levels, with relevance for daily life and sports activities where adaptation to external loads is required. Both phenomena—extremely low holding capacity and additional AF_{max} drop—were uncorrelated (r = -0.05), indicating that these represent two independent dimensions of muscle instability; both, however, appeared more often in female than male participants (AF-Ratio < 0.4: 9/13 female; AF_{max} unstable/stable < 0.7: 4/5 female).

In summary, possible influences on the absolute AF parameters are irrelevant as long as the same tester and setting are used for both conditions. The independence of the AF-Ratio from all factors considered eliminates the need for reference values and makes it a robust and universally applicable marker. This also allows for comparison between different studies.

4.3 Neurophysiological considerations of muscle stability

The following neurophysiological considerations are necessarily simplified given the complexity of the involved control networks, but outline the key mechanisms that may explain the observed phenomena.

The adaptive holding function requires a continuous sensorimotor feedback loop involving proprioceptive afferents (muscle spindle cells, Golgi tendon organs, joint and skin receptors) and a complex network of central structures including the sensorimotor cortex, thalamus, cerebellum, inferior olivary nucleus (ION), basal ganglia, and cingulate cortex [18,45–49]. A mixed feedforward-feedback control mechanism is assumed, in which the cerebellum—in cooperation with the ION—acts as a forward controller, predicting the sensory consequences of motor commands and enabling temporally coordinated adjustments [18,45,50,51]. For optimal AF execution, the system must continuously compare the intended motor command (efference copy) with the actual sensory feedback (reafference) and correct any mismatch by adjusting motor output [18,52].

This control architecture explains why the holding function is more demanding than pushing: during pushing actions, the force target is self-generated and does not require continuous adaptation to a varying external input, placing relatively lower demands on sensorimotor control. During holding actions—and particularly during AF assessment with an increasing external load—the system must constantly update its motor output based on changing sensory input, placing higher demands on the cerebellar-olivary timing circuitry and the proprioceptive feedback loop [18,21,45].

Crucially, several of the structures involved in this sensorimotor control network also process emotional, olfactory, and nociceptive information. The amygdala modulates motor responses to threat perception via connections to supplementary motor areas [53]. The anterior cingulate cortex integrates executive motor functions with emotional processing [49,54]. The cerebellum is

involved in both adaptive motor control [46,48] and olfactory processing [55,56]. Nociception directly affects motor output through spinal and supraspinal pathways [57]. The thalamus serves as a central integrative hub—far beyond a simple relay station—through which nearly all sensory, nociceptive, and limbic information must pass before reaching the cortex, while simultaneously receiving feedback from motor control structures including the cerebellum and basal ganglia [48,58–63]. This convergence of diverse inputs within a single central structure provides a plausible neuroanatomical basis for the observed effects of emotional, olfactory, proprioceptive, and nociceptive stimuli on adaptive motor control.

The instantaneous nature of the stability-instability switch is consistent with a reflexive mechanism operating through these fast-conducting pathways rather than through voluntary cognitive processes. The reproducibility of this response across the underlying studies—where adequate impairing stimuli consistently triggered instability and their removal restored stability—supports a stimulus-dependent reflexive mechanism. The long-loop latency of ~80–100 ms through the cerebellar-cortical circuits [52] would be sufficient for such rapid modulation. It is hypothesized that disruptive stimuli interfere with the target-actual comparison of muscle length and tension, disrupting the forward model and causing the system to fail at maintaining the isometric condition above a certain force threshold, i.e., readjusting length and tension adequately.

The gamma motor system may provide a specific mechanism for this selective impairment of holding capacity with preserved maximal force in response to disruptive stimuli. Under physiological conditions, alpha and gamma motor neurons are co-activated in a task-dependent manner, ensuring that muscle spindles remain sensitive during active contractions and continue to provide accurate length information [64]. This alpha-gamma coactivation is presumably calibrated by the cerebellum, which integrates efference copies of motor commands with spindle afference via spinocerebellar pathways [65]. Crucially, the tonic gamma drive is substantially regulated by the reticulospinal tract [66]. Its origin in the pontomedullary reticular formation serves as a convergence point for modulating input from stress-related axes, the autonomic nervous

system, and limbic structures [67,68], along with nociceptive afferents relayed via the spinoreticular pathway [66,69]. This pathway thus represents a physiologically plausible route through which psychovegetative states—including emotional distress, post-infectious dysregulation, and autonomic imbalance—as well as nociceptive input may alter gamma motor neuron excitability and, consequently, spindle sensitivity. A disturbance of this gamma-mediated calibration would specifically compromise the target-actual comparison of muscle length outlined above, leading to inadequate force adjustment and thus the observed instability during adaptive holding actions. This hypothesis is supported by the spindle manipulation experiments [31,32], in which selective disruption of spindle afference at the peripheral level reproduced the characteristic instability pattern without impairing peak force capacity—demonstrating that disturbed spindle-level proprioception alone is sufficient to produce the phenomenon. A central route converging on the same mechanism is indicated by the observation that emotional [33,34] and olfactory stimuli [35] as well as the Long COVID condition (associated with autonomic dysregulation) [36] elicited comparable instability, though the specific neural pathways involved remain to be established. While these proposed underlying pathways require further investigation, the convergence of spindle-level, spinal, and supraspinal mechanisms within the reticulospinal-gamma axis offers a parsimonious framework for the diverse stimuli observed to affect muscle stability.

The neurophysiological characteristics—high sensitivity, immediacy, and reversibility of the stability-instability switch—carry direct implications for screening, diagnostics, and the derivation of therapeutic measures, which are discussed below.

4.4 Implications for musculoskeletal complaints and non-contact injuries

Given the high prevalence of musculoskeletal complaints and non-contact injuries in the general population and athletes with enormous social and economic burden [70,71], suitable diagnostic, preventive and therapeutic approaches are urgently needed. Despite decades of research, the causes of musculoskeletal complaints and non-contact injuries remain insufficiently understood

549 and largely limited to the description of risk factors. Maximum strength and neuromuscular
550 imbalances have not proven to be reliable predictors [10,12–17]. The commonly cited concept of
551 'overload' cannot explain why complaints often arise unilaterally despite symmetrical loading, why
552 only a minority of athletes develop injuries under equal training conditions [72], or why well-trained
553 athletes develop complaints or non-contact injuries at all with normal exertion [73]. Load is
554 certainly a factor, but there must also be intrinsic factors related to load capacity. In the case of
555 insufficient resilience, a correlation of complaints and load would be reasonable.

556 A key observation is that non-contact injuries and musculoskeletal complaints predominantly
557 occur during activities requiring active deceleration and dynamic stabilization [1–10]—situations
558 in which muscles must hold or brake against external forces. Conventional strength assessments
559 using pushing actions without reactive components do not capture this adaptive holding function.
560 The present findings suggest that muscle instability—a reflexive, stimulus-dependent reduction of
561 the holding capacity—could represent a missing factor in this equation with high relevance in the
562 context of complaints and injuries. When the holding capacity is substantially reduced, the affected
563 muscle may become the weakest link in the kinetic chain, yielding prematurely under load and
564 exposing joint and connective tissue structures to increased stress which could plausibly result in
565 injuries and complaints. We propose the term functional instability syndrome (FIS) to describe this
566 mechanism. FIS remains a hypothetical construct that requires verification through prospective
567 clinical studies.

568 Several aspects of the present data support this hypothesis. First, the holding capacity reacted
569 sensitively and immediately to various disruptive stimuli, with clear reductions of on average 45 %.
570 Second, the response was reversible: stability was restored immediately after removal of the
571 impairing stimulus, presentation of a supportive stimulus or after targeted therapy—which speaks
572 for a mainly functional nature. Third, the between-subject effect for AF-Ratio regarding sex
573 approached significance (p = 0.060), with females showing descriptively lower values in the
574 unstable state (Fig 4C). Together with the first hints on higher vulnerability of female participants

575 (see 4.2), this may contribute to the well-documented higher injury rate in women [74–77]. In
576 general, the high variation of AF-Ratio in the unstable state indicates personal differences in
577 regulatory capacity and sensitivity in reaction to disruptive stimuli with some individuals reacting
578 particularly strongly, likely reflecting a higher susceptibility to complaints and injuries. Beyond such
579 individual predispositions, the instantaneous nature of the stability-instability switch further implies
580 that situational factors—such as acute emotional stress, pain, or sudden disruptive sensory
581 input—may transiently compromise stability even in otherwise unaffected individuals. This carries
582 particular relevance for sport, where such acute state shifts in critical moments could contribute to
583 sudden non-contact injuries. Fourth, the impairing effect of proprioceptive irritation and nociception
584 on muscle stability—investigated in [28,31,32,36] and illustrated by the presented case
585 examples—may explain the reported high re-injury rates, predominantly non-contact in nature
586 [12,14,78–80]. Structural damage such as hamstring strain [12], ACL rupture/reconstruction
587 [14,78], or concussion [80] can cause residual proprioceptive irritation and nociception even after
588 months, potentially reducing the holding capacity of muscles beyond the directly affected area
589 (shown by case examples) and thereby increasing vulnerability to injury under load. This is further
590 supported by a recent study on football players actively participating in training (submitted)
591 showing a high association between stability deficits and musculoskeletal complaints as well as
592 by the study on Long COVID patients with a high incidence of musculoskeletal complaints [36,37].
593 Fifth, the connection of psychosocial stress and musculoskeletal complaints is well-known yet a
594 plausible explanation is lacking [81–85]—here too, a reduced holding capacity caused by
595 emotional stressors could provide an explanation. Further investigations are justified and needed.

596 The evidence to date suggests that the use of muscle stability in the sense of AF—with its special
597 characterization of being highly sensitive with immediate response to supportive or impairing
598 stimuli—has high potential as tool for screening, prevention, targeted diagnostics and AF-guided
599 therapy derivation. The AF-guided therapeutic approach—in which individualized interventions are
600 selected based on their ability to restore muscle stability—has been described previously in Long

601 COVID patients [36,37] and was used for restoring muscle stability in Cases 2 and 3 presented
602 here, showing high potential for individualized treatment. This approach is highly personalized,
603 with a focus on identifying and addressing the underlying individual causes of the condition. This
604 warrants further clinical investigation. It is hypothesized that muscular instability may represent a
605 necessary—though not necessarily sufficient—condition for the development of musculoskeletal
606 complaints and non-contact injuries.

607 Regarding prevention, two aspects should be addressed: First, the holding capacity reacts early—
608 even in asymptomatic participants—making it suitable for screening before complaints or injuries
609 arise. Second, the reflexive nature of the instability response implies that muscle stability cannot
610 be trained directly in the conventional sense. However, two complementary strategies emerge: (1)
611 identification and elimination of individual disruptive stimuli leading to instability through AF-guided
612 diagnostics and cause-related individualized therapy, and (2) optimization of the adaptive holding
613 and braking function through targeted training programs. For example, a preventive effect on
614 hamstring strain injuries was suggested—although still debated—for the Nordic hamstring
615 exercise [86–90], which includes adaptive components and may improve Adaptive Force. Cases
616 with limited effectiveness could indicate the presence of an underlying cause that affects the
617 holding capacity and cannot be resolved by exercise. Further research should address these
618 aspects.

619 In summary, the concept of muscle stability shifts the focus from load to individual resilience: not
620 strength decides, but whether the neuromuscular system can maintain adequate control under
621 external loads. Given the limited value of strength screening for injuries and complaints, the AF
622 assessment offers a novel framework addressing a neuromuscular function challenged during
623 injury-prone movements. The concept provides plausible explanations for still unsolved problems
624 in sports science and medicine and offers a tool for screening, targeted diagnostics and therapy
625 derivation.

4.5 Limitations and methodological aspects

Limitations of the underlying studies are discussed in the respective articles. The present analysis used pre-sorted data from six studies to identify common characteristics of stable and unstable muscles. This approach does not allow conclusions about stimulus-specific responses (reported in the original studies). The present sample, though sufficient for identifying fundamental characteristics, is limited in size and diversity. Generalizability to other populations (e.g., different age groups, sports, pathologies) requires verification.

The effects of tester and participant characteristics on absolute AF values could not be fully disentangled due to the non-balanced tester-participant constellation, as discussed above. Although tester strength could limit the test, the tester can use the entire body to apply force, while the participant's muscle or muscle group is largely isolated—making the tester's maximal strength subordinate to the test outcome. Furthermore, given the often significant instability associated with impaired muscles, the strength demands placed on the tester are usually moderate. Future studies should systematically examine tester-specific influences with a larger number of testers. The limited pectoralis data (n = 3) and the methodological specificity of the break point detection via angular velocity warrant further investigation with larger samples and refined data processing for muscles with long lever tests (strong oscillations). The AF-Ratio threshold of 0.90—used here to verify agreement between clinical assessment and objective data—represents a preliminary boundary. Future studies with larger and more diverse samples should establish validated cut-off values and their clinical relevance in independent samples.

Furthermore, the present analysis is cross-sectional in nature. Prospective studies are needed to establish whether muscle instability—as assessed by AF—predicts the occurrence of musculoskeletal complaints or injuries. Clinical studies are required to evaluate the effectiveness of AF-guided diagnostics and individualized therapy derivation.

5 Conclusion

Stable and unstable muscles can be clearly distinguished by AF parameters. Unstable muscles are not weak—they fail to access their full force capacity isometrically but generate comparable or higher forces during the subsequent eccentric phase. The deficit is one of neuromuscular control, not of strength. Based on the findings, we propose the concept of functional instability syndrome (FIS) as a hypothetical mechanism linking muscle instability to musculoskeletal complaints and non-contact injuries. Shifting the perspective from strength to muscle stability and from load to individual resilience may provide a more adequate framework for understanding, preventing, and treating musculoskeletal disorders and non-contact injuries.

The holding capacity reacts early, sensitively and instantly to disruptive stimuli and is restored equally rapidly upon their removal, supporting a reflexive, stimulus-dependent mechanism consistent with the shared neural substrates for motor control, proprioception, nociception, and emotion—providing a plausible theoretical basis for the findings and for practical implications. The AF-Ratio is self-referenced to the muscle's own peak force, requiring no external reference values, and independent of muscle group, tester, participant sex, and experimental type. These characteristics suggest a broad applicability of AF assessment with high potential as a valuable tool for screening, prevention, targeted diagnostics and individualized therapy derivation. Further studies with larger and more diverse samples are needed for verification and to establish the clinical value of AF-guided approaches.

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