From strength to stability: Proposal for a changed perspective on the mechanisms of musculoskeletal complaints and non-contact injuries—a synthesizing reconsideration of previously collected data on muscular holding capacity

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Abstract

Musculoskeletal complaints and non-contact injuries remain poorly understood. The pushing maximum strength usually examined does not represent the muscle action at which injuries occur: when muscles hold or brake under load. This study focuses on the new approach of muscle stability (Adaptive Force; AF)—the capacity to adapt to increasing external loads. To obtain a comprehensive picture of this unique muscle function, its special features and to demonstrate practical applications, the available AF data are synthesized and re-evaluated supplemented by single cases. AF data from 481 stable and 307 unstable trials of 112 muscles (elbow/hip flexors, pectoralis major) from six studies were included. All studies used an objectified manual muscle test to assess AF in both conditions (stable/unstable) in identical muscles. The respective conditions were elicited by various interventions. The maximum AF (AF_{max}; peak force), the maximum isometric AF ($AFiso_{max}$; holding capacity), AF at onset of oscillations (AFosc) and their ratios were analyzed by a mixed ANOVA between stable and unstable muscles including the factors muscle, tester, participant's sex and experiment. Unstable muscles had highly significant reduced $AFiso_{max}$, but higher AF_{max} and AFosc. The relative holding capacity was ~56% in unstable and ~99% in stable state. The absolute parameters showed an interaction effect for 'tester'—probably a design artifact. The relative AF parameters were robust to all factors. The results indicate muscles are not weak in response to impairing stimuli (higher AF_{max} during lengthening), but unstable: they are unable to generate their full force in static position and yield at clearly submaximal forces. This most likely destabilizes joints under load which could be a key factor in injury and complaint development. Muscles can immediately switch between stability and instability in response to various stimuli. This makes the

AF a valuable tool for personalized diagnostics and therapy derivation. We suggest shifting the focus from strength to stability and from load to resilience. The robustness of the relative holding capacity makes it independent of reference values, thus offers the properties of a gold standard. Further studies are required to validate the approach.

1 Introduction

Since decades muscle function has been assessed to investigate possible causes of injuries or complaints by measuring muscular strength or other parameters (e.g., electromyography) during different muscle actions (concentric, isometric or eccentric). However, until now sports and movement sciences as well as medicine could not unravel the enigma of musculoskeletal injuries or complaints. Non-contact injuries occur when "the muscle develops tension while lengthening" (1), when inertial forces are to be counteracted often enhanced by additional gravitational effects (2–5). Despite this knowledge, muscle function is usually assessed while pushing against resistance. Clear differences between patients and controls have not been found in those parameters until now. Although the right questions are asked—e.g., why do athletes suffer from injuries or complaints although they are well trained? — answers are pending. The maximal strength cannot be the cause since the athletes clearly have no strength problem. Some argue that 'neuromuscular imbalances' might be a key factor (6) such as altered lower limb biomechanics during jump-landing tasks (7) or strength asymmetries (8). However, the review of Liu et al. demonstrated inconsistent results on the relation of strength imbalances and injury risk (at least for hamstrings) (9). Thus, despite numerous research studies, the theoretical basis of risk factors such as strength imbalances is still lacking (9). We suggest shifting the focus from strength or power to muscular stability. Muscular stability is understood as capacity to resist constant or variable external loads in a holding manner. We inaugurated the term Adaptive Force (AF) to describe this neuromuscular function (10–19). AF is based on holding isometric muscle actions (HIMA). A recent review comparing HIMA and pushing isometric muscle actions (PIMA) showed that those isometric types can be distinguished by objective measures and that HIMA seems to require more complex control strategies than PIMA (20). For AF assessment, the participant should not only 'hold' a constant external load but adapt to an increasing load while maintaining a position (HIMA). The adaptive nature of this task challenges the neuromuscular system even more. Muscular stabilization under load is necessary to keep joint structures aligned to each other during motor actions in sports or daily activities. An adequate adaptation of the neuromuscular system to the actual load is required to provide such protective stabilization. However, the holding capacity is rarely considered in science or diagnostics.

As demonstrated by a range of studies, this muscle function can be regarded as unique (11,12,12,14–16,19,21–23). In contrast to muscle strength in the traditional sense (PIMA, concentrics), there is clear evidence that the adaptive holding capacity (AF) can be instantly impaired by interfering influences, leading to instability (14–19,21). This means that one and the same muscle can switch back and forth between the two states, the stable and the unstable. Several studies have shown that AF is vulnerable to disruptive emotional interventions (14–16), but also to specific pre-conditioning intended to manipulate muscle spindle cells (19,21). AF-data from Long COVID patients showed impaired muscle stability, which returned to stability after treatment and recovery (17,18). Furthermore, single case studies indicate an influence of nociception on AF (22). In all these studies the AF of the same muscles was measured during the unstable (impaired) and during the stable (unimpaired) state. This opens the opportunity of pooling data from a linked sample of muscles in both conditions, taken from different studies.

To obtain a comprehensive picture of this particular muscle function and to highlight its special characteristics, this article will synthesize the available data on the holding capacity to describe stable vs. unstable adaptation, i.e. muscle stability vs. instability. The main focus will lie on the data of healthy participants (14–16,19) and long COVID patients (17,18). Case studies on AF in nociception (22) and mental stress (14) are also presented, which are intended to demonstrate particular relevance for practical application. On this basis, the article also aims to provide suggestions for the use of muscle stability in diagnostics, injury prevention, and the derivation of therapy and rehabilitation.

2 Material and Methods

The AF data available to date from a total of six studies with healthy participants (14–16,19,21) and long COVID patients (17) are merged and analyzed for the study presented here, complemented by the data from single cases. The AF is always compared for identical muscles between their stable (unimpaired) and unstable (impaired by certain stimuli) state. All measurements have been performed at the Neuromechanics Laboratory of the University of Potsdam. The AF of elbow and hip flexors as well as pectoralis major muscle were assessed by an objectified manual muscle test (MMT) executed by two experienced testers (tester A: m, 63-65 yrs., 185 cm, 87 kg, 27 yrs. of MMT experience; tester B: f, 34-35 yrs., 168 cm, 55 kg, 8 yrs. of MMT experience).

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., complaint-free; 28 m, 26 f; 30 ± 11 yrs., range: 19-70) and participated in the experiments that should provoke instability or stability with unpleasant vs. pleasant imagery (14,15) or odor perception (16) and with muscle spindle conditioning (19,21). 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 (17). Four further participants are considered as single cases (2 m, 2 f). They were not included in statistical evaluation, however, they are described and discussed in the respective sections.

Inclusion criterion for the statistical analyses was the availability of clear stable and unstable trials for at least one muscle per participant. This classification was based on the assessment of the experienced testers in the respective studies (not on the acquired data; details see ‘procedure'). In total, 56 elbow flexors, 53 hip flexors and 3 pectoralis major muscles were considered for evaluation. (The authors are aware that also for pectoralis major muscle there is a muscle group involved. For simplification we use the term ‘pectoralis major’).

The studies on which this article is based on were conducted according to the guidelines of the Declaration of Helsinki and was approved by the Ethics Committee of the University of Potsdam, Germany (protocol code 35/2018; 17 October 2018). All participants gave their written informed consent to participate.

2.2 Technical equipment

The MMTs were objectified by a wireless handheld device, which was described in detail in the underlying studies (14–17,19). 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%) simultaneously recorded the reaction force and angular velocity

during the MMTs (sampling rate: 180 Hz). The data were AD converted and transmitted via Bluetooth to a tablet (Sticky notes, comp.: StatConsult, Magdeburg, Germany).

2.3 Manual Muscle Tests and settings

The AF parameters were assessed during standardized manual muscle tests (MMTs) objectified by the handheld device. The MMTs were performed in the sense of a break test as was previously described (14–17,19). The tester applied a standardized increasing force [see (14–17,19)] on the participant's limb by pushing against it in the direction of muscle lengthening. The task of the participant was to maintain the starting position for as long as possible performing a HIMA. Hence, they had to adapt to the increasing force in a static position. In addition to the objective data recorded by the handheld device, the testers rated the MMT either as 'stable' or as 'unstable' in dependence of the ability of the participant to maintain the starting position despite the force increase. In general, a 'stable' muscle in MMT is present if the limb of the participant stays in the static starting position until a considerably high force level is reached. This reflects adequate adaptation. An 'unstable' muscle in MMT is characterized by a muscle lengthening during submaximal intensities; thus, if the limb gives way during the external force rise. In this case, the adaptation is inadequate. During the occurring eccentric phase, the force usually continues to increase until the peak force is reached.

The detailed settings and procedures of the individual experiments can be found in the corresponding publications (14–17,19). Since the MMTs were performed similarly, the main setting should be described briefly: the participants lay supine for all MMTs. Elbow and hip joints amounted to 90° for elbow and hip flexor tests, respectively. For pectoralis major, the elbow was fully extended, shoulder forward flexion amounted to 90° with maximal internal rotation. The contact of the tester with the handheld device positioned in their palm was at the distal forearm or thigh, respectively. The test vectors were aligned to the direction of muscle fibers. The contact points were marked for standardization purposes to secure equal intra-individual point of force application during the different trials.

2.4 Procedure

As mentioned above, the data of six different studies were included here. Although the AF assessment was identical, the interventions differed, i.e., the approach to investigate possible alterations of muscle stability. Regarding the studies in healthy participants, two studies compared pleasant (tasty) vs. unpleasant (disgusting) food imaginations (14,15), one further study investigated pleasant vs. unpleasant odors (16), and in two other studies a physiological muscle spindle adjustment was compared to a provoked slack of muscle spindles [either by a specific contraction-shortening procedure: contraction in lengthening position with passive return (19) or by manipulation (21)]. One further study measured AF in long COVID patients in disease state, after first treatment and after recovery (17). In all studies two to three trials were performed per muscle and condition. Three studies of healthy participants (14,16,19) included additional baseline measurements. According to the hypotheses of the underlying studies, most participants showed stable MMTs for baseline, pleasant imaginations/odors, physiological muscle spindle and after treatment/recovery and, in contrast, unstable MMTs for the trials with unpleasant imaginations/odors, muscle spindle slack and in Long COVID state. For the present investigation all trials were included for which the testers' rating of the MMT was clearly 'stable' or 'unstable'. Since only the clinically rated muscle state (stable or unstable) is relevant here (not the experimental method approach), the trials in which the hypothesis of the underlying studies was not fulfilled (~3%) were also sorted into the categories 'stable' or 'unstable' for the subsequent evaluation. This applies to six trials that were stable, although instability was hypothesized and 17 unstable trials, although stability was assumed.

A total of 481 stable trials (238 elbow flexors, 232 hip flexors, 11 pectoralis major) and 307 unstable trials (150 elbow flexors, 148 hip flexors, 9 pectoralis) were included in the present analyses. The tests of all stable muscles and all unstable muscles were combined—regardless of which of the three muscles was involved. Since the evaluation is based on a relative comparison of stable and unstable states of identical muscles, this is permissible. Post-hoc analyses will evaluate, inter alia, the differences between muscles.

2.5 Data processing and statistical analyses

The data has already been processed in the underlying studies. The corresponding values were used for the present analysis. The data processing used force and gyrometer signals and was done in NI DIAdem 2017 (National Instruments, Austin, TX, USA) [for detailed description see underlying studies (14–17,19,21)]. The basic parameters should be briefly described (Figure 1):

1. AF_{max} (N): peak value of the whole trial. This could be reached either under static conditions or during muscle lengthening.
2. $AFiso_{max}$ (N): highest force value under static conditions. It refers to the maximum force of the isometric holding phase. This does not necessarily refer to a peak value. The gyrometer signal was used to detect a limb movement in direction of muscle lengthening (breaking point). In case the static condition was maintained during the whole trial, $AFiso_{max} = AF_{max}$. If a continuous deviation from the zero line was detected in the angular velocity (indicates yielding) the force value corresponding to the last zero crossing of the gyrometer signal referred to $AFiso_{max}$ (Figure 1).
3. AFosc (N): force at the onset of a clear upswing of mechanical oscillations in force signal (at least 4 consecutive maxima with time distance dx < 0.15s). Without a clear upswing of oscillations, AFosc = AF_{max} (Figure 1).

A conversion to torque was not made, as the AF values of the same muscle and thus same lever length were compared with each other.

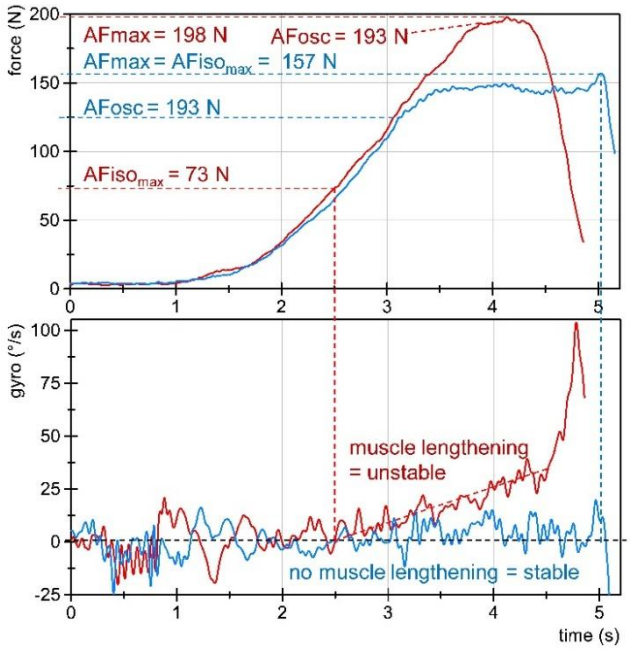

Figure 1. *Exemplary curves of the same muscle in comparison of stable (blue) and unstable (red) state. Displayed are the signals of force (above) and angular velocity (gyro; below) of two MMTs of the elbow flexors of one healthy participant*

(female, 24 yrs.) during food imagination. The MMTs were performed by the tester B. For tasty imagery, the muscle stayed stable during the whole test (stable, blue), whereas for disgusting imagery the muscle started to lengthen on a clearly submaximal force level (unstable, red) but reached a higher peak force during lengthening. With stability the oscillations in force signal arose at a submaximal level. During unstable MMT, oscillations remained absent until near the peak force. The slopes of force increase are 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).

Furthermore, the ratios $\frac{\mathrm{AFiso_{max}}}{\mathrm{AF_{max}}}$ and $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$ were computed and used for evaluation. The latter indicates if the oscillations arose before (< 1) or after (> 1) a potential breaking point. In the underlying studies, the slope of force rise was additionally considered. This served as parameter securing comparability between the MMTs. Since the slope between the stable and unstable states did not differ significantly, the prerequisite (similar force increase) for the comparison of the AF parameters was already met there and is not considered again here.

The 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 or unstable), muscle and participant and were used for further evaluation.

Statistical comparisons were done using SPSS Statistics 29 (Windows, Version 28.0. Armonk, NY, USA: IBM Corp). For a first impression of the overall questioning—if stable and unstable trials differ—t tests for paired samples were performed for all parameters (AF_{max}, $AFiso_{max}$, AFosc and their ratios). To include different factors, a mixed-model ANOVA was additionally performed to evaluate the AF parameters regarding the muscle state ('stability' = stable vs. unstable) with factors muscle (elbow flexor, hip flexor, pectoralis muscle), tester (tester A, tester B), experiment (imaginations, odors, spindle-procedure, spindle-manipulation, Long COVID) and participants' sex (female, male). Normality of difference scores (Kolmogorov Smirnoff Test) was fulfilled for all parameters except for $AFiso_{max}$ ($p = 0.038$) and $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$ ($p < 0.001$). However, according to Salkind the normality assumption of the difference score can be violated in sample sizes > 30 (24). Hence, statistical comparisons were performed for all parameters using parametric tests. Since only slight outliers existed (> 1.5-fold and < 3-fold of interquartile range) no values were excluded. For mixed ANOVA, Mauchly-Test of sphericity was non-significant for all parameters. Since the variance homogeneity (Levene test) was not fulfilled for $AFiso_{max}$ and AFosc the main effects of interactions should not be interpreted, but the post-hoc comparisons can be (25). In case of a significant effect for within-subject factors, Welch-ANOVA was performed as it is robust against violations of homogeneity. Post-hoc tests were Bonferroni corrected. For significant between-subject factors, t tests were performed instead of a repeated measures ANOVA since only two groups (stable vs. unstable) existed. Effect sizes eta-squared (η^2) and Cohen's *d* were used. Eta-squared was interpreted as small (0.01–0.059), moderate (0.06–0.139) and large (≥ 0.14) and Cohen's *d* as small (0.2–0.49), moderate (0.5–0.79), large (0.80–1.29) and very large (≥1.3) effects (26). The significance level was $\alpha = 0.05$.

3 Results

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

Table 1 displays the M, SD and range of all parameters comparing stable vs. unstable muscles, including the results of the paired t tests. Figure 2 additionally illustrates the respective 95% confidence intervals.

Table 1. *Arithmetic means (M) and standard deviations (SD) of AF parameters for stable vs. unstable muscles (n = 112). Results of paired t test (t value, significance p, effect size Cohen's d) are given. df = 111 for all comparisons.*

parameter	muscle state	M	SD	range (min – max)	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			
ratio $AFiso_{max}/AF_{max}$	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			

AF_{max} = max. Adaptive Force; $AFiso_{max}$ = max. isometric AF, AFosc = AF at onset of oscillations

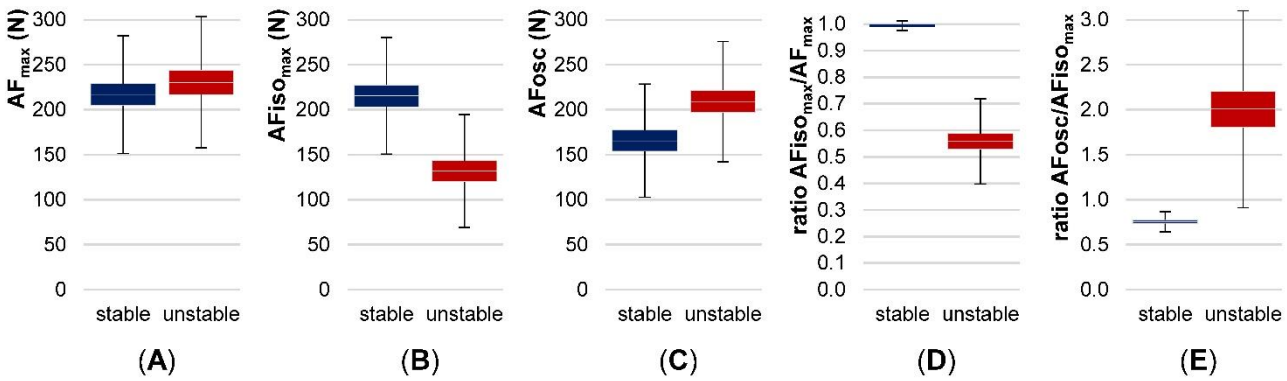

Figure 2*. 95%-confidence intervals including arithmetic means and standard deviations (error bars) of the AF parameters (in N) and their ratios (relative values) for stable (blue) and unstable (red) muscles: (**A**) max. AF (AF_{max}), (**B**) max. isometric Adaptive Force ($AFiso_{max}$), (**C**) AF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

$AFiso_{max}$ was clearly and significantly lower for unstable vs. stable muscles with a very large effect of $d = 1.9$. AF_{max} was significantly higher for unstable vs. stable and showed the lowest effect ($d = 0.4$). It is important to mention that AF_{max} was reached during muscle lengthening for unstable muscles and under static conditions for stable muscles. This is reflected by the ratio $\frac{AFiso_{max}}{AF_{max}}$, which showed the highest effect size ($d = 2.7$). This clear difference is visible in Figure 2D. $AFiso_{max}$ amounted averagely 55.8 ± 16 % of AF_{max} for unstable muscles and 99.4 ± 1.8 % for stable ones (Table 1). This indicates that the participants were not able to stabilize the static position up to their maximum force capacity in unstable conditions. Nevertheless, they were able to generate their full force, but only during muscle lengthening. In contrast with stable conditions, the participants were able to reach their maximum force during adaptation to an external load in a static position.

Categorizing the results of the ratio $\frac{AFiso_{max}}{AF_{max}}$ of all single trials in arbitrarily determined percentage ranges (Figure 3), 96% of all stable trials (464 of 481) showed values between 0.95 and 1, where only 0.4% (2 of 481) were below 0.8. For unstable trials the assignment was reverse: 90% (275 of 307) showed $\frac{AFiso_{max}}{AF_{max}} < 0.8$ 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).

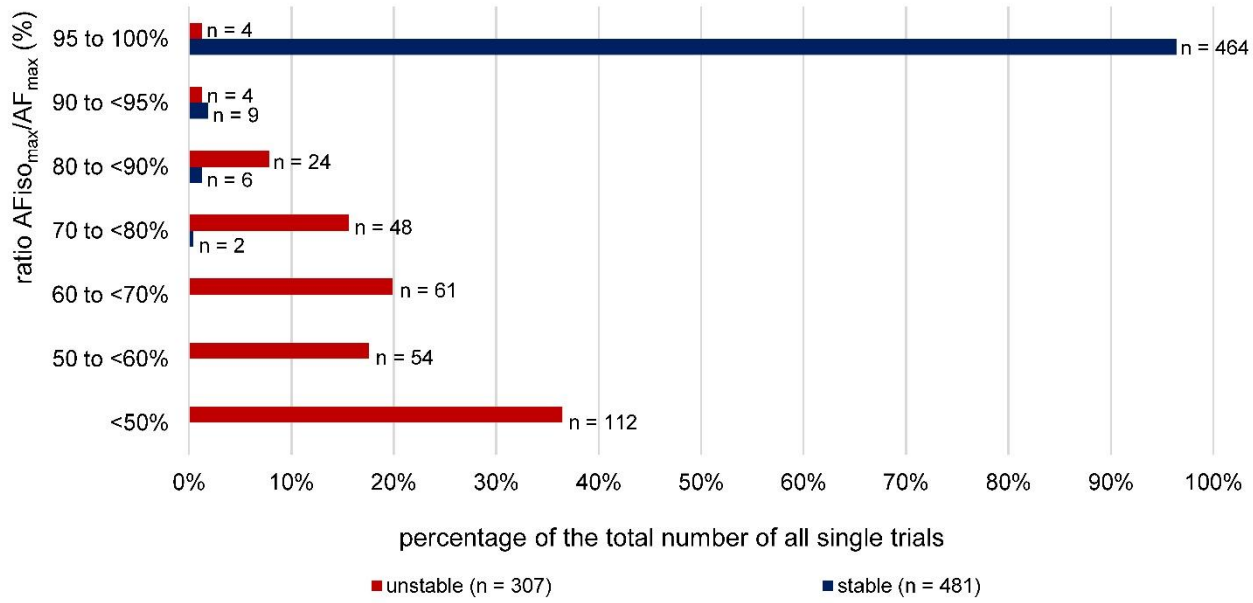

Figure 3. *Number of single trials of the relative holding capacity (ratio AFiso$_{max}$/AF$_{max}$) categorized in percentage ranges for stable (n = 481) and unstable (n = 307) muscles.*

AFosc was significantly higher for unstable vs. stable muscles (d = 1.3). The ratio $\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$ indicated that for stable muscles the upswing of oscillations occurred before reaching AFiso$_{max}$ in 469 of 479 trials (98%) ($\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$ <1; Table 1, Figure 2E). Five of 479 trials were = 1 (1%) and 5 trials > 1 (1%; M of these five trials $\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$ = 1.055). For unstable muscles—in case oscillations arose at all—they appeared after the breaking point in 280 of 306 trials (91.5%) ($\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$ > 1; Table 1, Figure 2E). 88 of 306 trials (29%) showed no oscillatory upswing at all (AFosc = AF$_{max}$). For stable muscles this was only the case in 5 of 479 trials (1%). However, unstable muscles showed in 26 of 309 trials (8.5%) an upswing of oscillations before AFiso$_{max}$ (averaged $\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$ = 0.85).

3.2 Comparison of AF parameters regarding possibly confounding factors

Figure 4 illustrates the M and SD of each AF parameter separated for the different factors (muscle, tester, participants' sex, experiment) and classified according to the muscle state (stable, unstable). The mixed-model ANOVA revealed a clear significant main effect for the muscle state 'stability' (stable vs. unstable) on all AF parameters. Table 2 shows the results of within-subject effects (note: AFiso$_{max}$ and AFosc should not be interpreted due to variance heterogeneity). From the interpretable effects, solely the tester seems to have a significant effect on AF$_{max}$ ($F(1, 89) = 4.631$, $p = 0.34$, $\eta^2 = 0.049$). Importantly, no factor had a significant effect on the ratio $\frac{\text{AFiso}_{\text{max}}}{\text{AF}_{\text{max}}}$ and $\frac{\text{AFosc}}{\text{AFiso}_{\text{max}}}$. Furthermore, there was a significant within-subject interaction for AF$_{max}$ regarding stability*sex*experiment ($F(2, 89) = 3.750$, $p = 0.027$, $\eta^2 = 0.078$). All other factor combinations showed no significant within-subject interactions ($p > 0.05$). The between-subject effects will be described below separated by factors. There were no significant effects for multiple factor comparisons ($p > 0.05$).

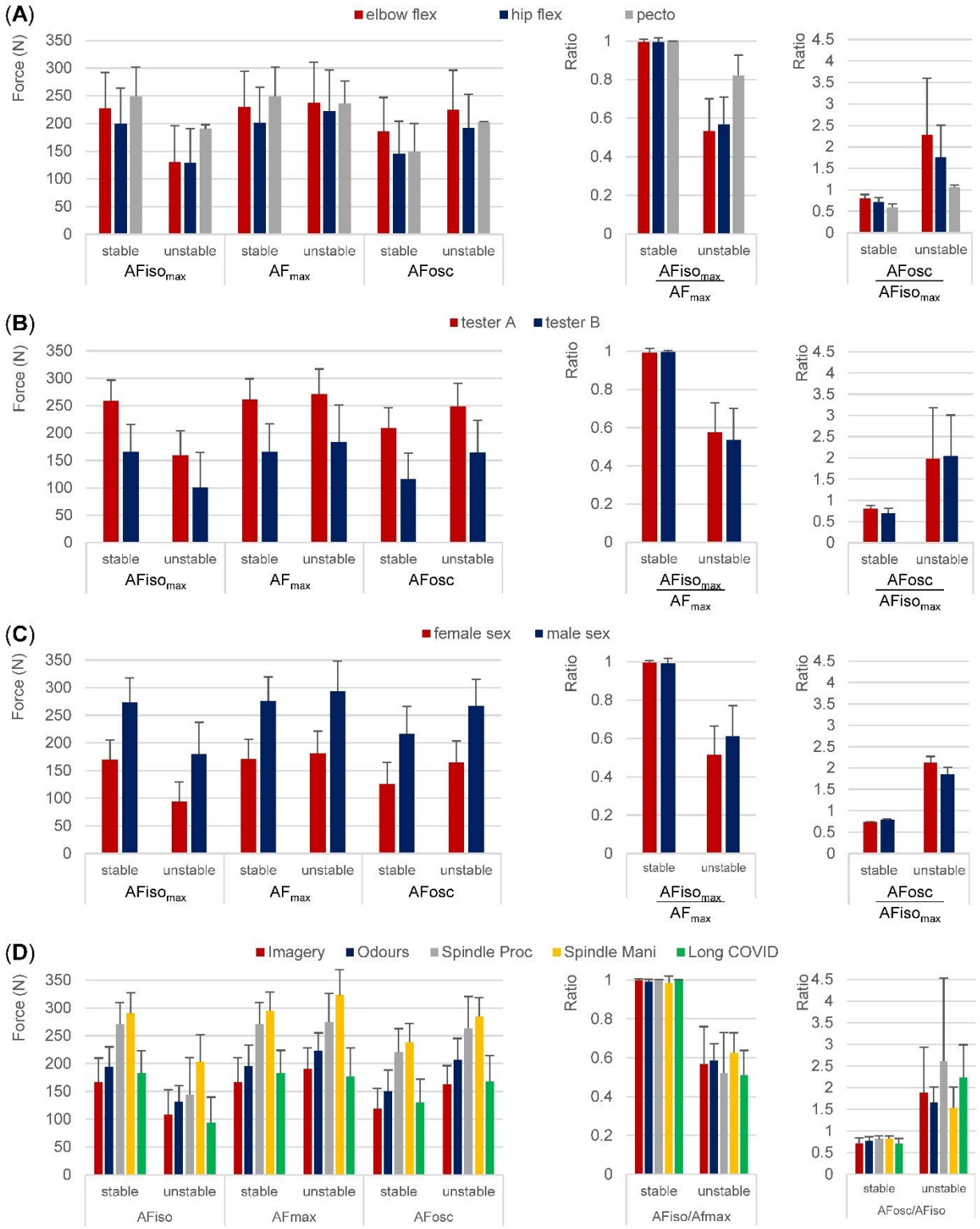

Figure 4. *Arithmetic means and standard deviations of the parameters maximal isometric Adaptive Force (AFiso$_{max}$), max. AF (AF$_{max}$), AF at onset of oscillations (AFosc) (all in N) and their ratios regarding the factors* ***(A)*** *tested muscles,* ***(B)*** *testers,* ***(C)*** *sex of participants and* ***(D)*** *performed experiment. The values are categorized in stable and unstable muscles for each factor and parameter. Abbr: flex = flexors, pecto = pectoralis muscle, proc = procedure, mani = manipulation.*

Table 2. *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 major), tester (A, B), participants' sex (female, male), and experiment (imagery, odors, spindle manipulation, spindle-procedure, Long COVID).*

	AFisomax	AFmax	AFosc	$\frac{AFiso_{max}}{AF_{max}}$	$\frac{AFosc}{AFiso_{max}}$
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 (<0.000)
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)

AF_{max} = max. Adaptive Force; $AFiso_{max}$ = max. isometric AF, AFosc = AF at onset of oscillations.
Significant results are in bold.

3.2.1 Differences regarding assessed muscles

None of the AF parameters showed a significant within-subject interaction for stability*muscle (Table 2). This is also reflected by Figure 4A where the behavior of the AF parameters is similar for each muscle with respect to stable and unstable muscles. Figure 5 illustrates the averaged values of the ratio $\frac{AFiso_{max}}{AF_{max}}$ (M of single trials) in ascending order for each muscle measured, categorized in muscle groups with respect to stable and unstable trials. This depicts a similar behavior especially for elbow and hip flexors. It should be particularly emphasized that for the unstable state in some cases, the holding capacity drops massively to below 50% (13 of 53 hip flexors (24.5%); 22 of 56 elbow flexors (39.3%); this applies to 112 of 306 cases from single trials). In 36 out of 306 single trials (12%) the holding function even falls below 30% of the maximum force. For the three pectoralis muscles tested the values for unstable trials (light green circles) were comparatively high. This results in a wide range of the ratio ($\frac{AFiso_{max}}{AF_{max}}$ = 0.103 to 0.914) in the unstable state also reflected by the CV of 28.7% (elbow: 31%, hip: 25%, pecto: 13%). For the stable condition the CV amounts to 1.8% (elbow: 1.4%, hip: 2,2%, pecto: 0%).

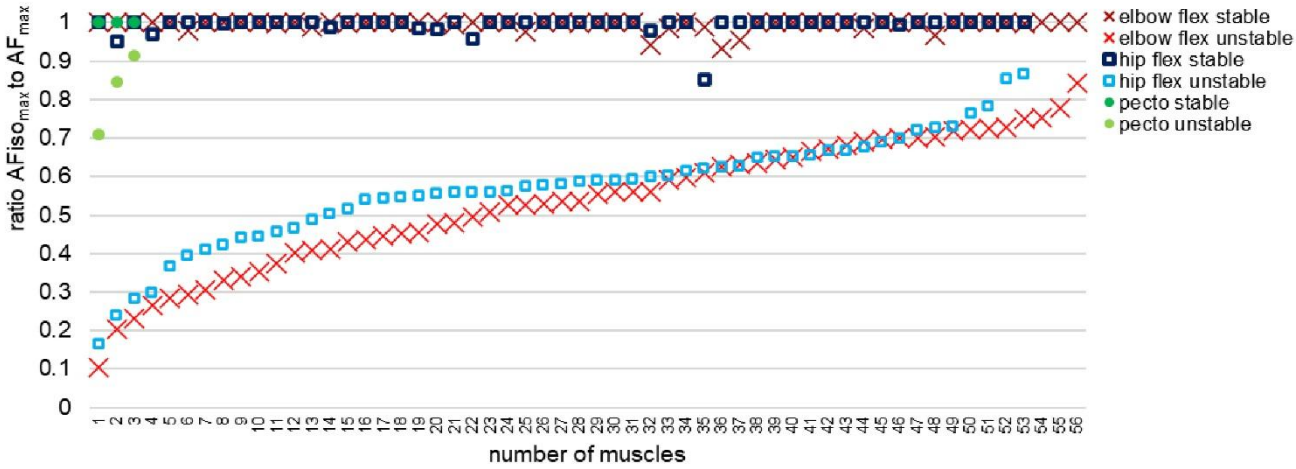

Figure 5*. Arithmetic means of the ratio maximal isometric Adaptive Force ($AFiso_{max}$) to maximal AF (AF_{max}), sorted in ascending order for the trials of each muscle tested (elbow flexors = red cross, hip flexors = blue square, and pectoralis major = green circle) and muscle state (stable = dark and unstable = light).*
Note: all trials of one muscle in the respective condition were averaged.

3.2.2 Differences regarding testers

The within-subject interaction for stability*tester was significant for $AFiso_{max}$, AF_{max} and AFosc (Table 2, Figure 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 $p < 0.001$). The ratios $\frac{AFiso_{max}}{AF_{max}}$ and $\frac{AFosc}{AFiso_{max}}$ did not differ significantly.

Between-subject effects (regardless of whether stable or unstable) were significant for $AFiso_{max}$ ($p = 0.048$, $\eta^2 = 0.043$), AF_{max} ($p = 0.012$, $\eta^2 = 0.068$) and AFosc ($p = 0.004$, $\eta^2 = 0.088$). Pairwise comparisons of mixed ANOVA revealed significantly lower values for the female vs. male tester for $AFiso_{max}$ ($p = 0.001$, MD = –69.48, 95%-CI: –89.909 to –48.946), AF_{max} ($p < 0.001$, MD = –68.70, 95%-CI: –89.07 to –48.33) and AFosc ($p < 0.001$, MD = –51.40, 95%-CI: –70.52 to –32.27).

Comparing stable vs. unstable muscles within female and male tester, respectively, RM ANOVA 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). Due to non-significant between-subject effects the other AF parameters were not considered in RM ANOVA.

3.2.3 Differences regarding sex of participants

None of the AF parameters showed a significant interaction for stability*sex. Between-subject effects were significant for $AFiso_{max}$ ($p < 0.001$, $\eta^2 = 0.215$), AF_{max} ($p < 0.001$, $\eta^2 = 0.218$) and AFosc ($p < 0.001$, $\eta^2 = 0.202$), not for the ratios ($\frac{AFiso_{max}}{AF_{max}}$: $p = 0.060$, $\eta^2 = 0.039$ and $\frac{AFosc}{AFiso_{max}}$: 0.487). Tukey 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 to –48.9), AF_{max} ($p < 0.001$, MD = –68.7, 95%-CI: –89.1 to –48.3) and AFosc ($p < 0.001$, MD = –61.4, 95%-CI: –70.5 to –32.3). Although $\frac{AFiso_{max}}{AF_{max}}$ was only just not significant for between-subject effects, post hoc test revealed a significantly lower ratio for females vs. males ($p = 0.004$, MD = –0.71, 95%-CI: –0.12 to –0.24). As visible in Figure 4C, the ratio $\frac{AFiso_{max}}{AF_{max}}$ was similar for stable muscles comparing the sexes, whereas female participants revealed a lower ratio for unstable muscles. RM ANOVA separated by participants' sex comparing stable vs. unstable muscles revealed significant results for all AF parameters, where AF_{max} showed the smallest effect with significantly lower values for stable vs. unstable muscles (female and male: MD = –10.5 and –17.7, $p = 0.022$ and $p < 0.001$, $d = 0.29$ and 0.58). $AFiso_{max}$ showed significantly higher values for stable vs. unstable muscles (female and male: MD = 75.7 and 93.74, $p < 0.001$, $d = 2.02$ and 1.87). AFosc showed significantly lower values for stable vs. unstable for both sexes (female and male: MD = –38.15 and –50.41, $p < 0.001$, $d = 1.16$ and 1.58). The ratio $\frac{AFiso_{max}}{AF_{max}}$ showed the largest effect with significantly higher values for stable vs. unstable (female and male: MD = 0.48 and 0.38, $p < 0.001$, $d = 3.27$ and 2.35).

3.2.4 Differences regarding experiments

Mixed ANOVA showed no significant within-subject interaction of stability*experiment (Table 2. Figure 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 showed also 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.

RM ANOVA revealed significantly higher AF_{max} values in the unstable state compared to the stable state 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, $p = 0.277$) (Figure 6). AFosc was significantly higher for unstable vs. stable muscles in all experiments (MD range: –55.97 to –37.53, $p \leq 0.001$, d = 1.03 to 2.82).

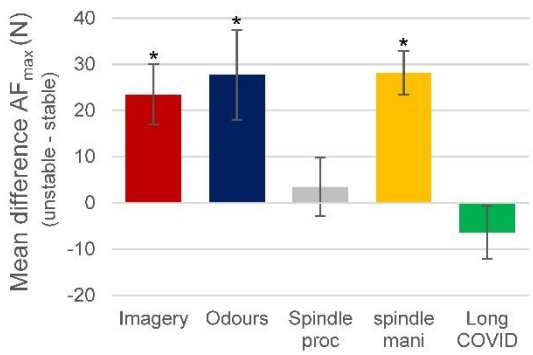

***Figure 6**. Mean differences and standard error (SE) of AF_{max} for each experiment. Positive values indicate a higher AF_{max} for unstable vs. stable state. *p < 0.02*

Summarizing the results briefly, stable vs. unstable muscles differ significantly regarding all AF parameters regardless of factors muscle, participants' sex and experiments. The factor 'tester' only had a significant influence on 'stability' for the absolute AF parameters, with the female tester showing lower values than the male tester—probably a design artefact, which is discussed below. Regardless of 'stability', 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. It is crucial to note that the ratios $\frac{\mathrm{AFiso_{max}}}{\mathrm{AF_{max}}}$ and $\frac{\mathrm{AFosc}}{\mathrm{AFiso_{max}}}$ demonstrated no significant interaction effects.

3.3 Single cases: AF in individuals with mental stress, nociception, and particularly clear reaction during emotional imagery

Further AF data were collected in the context of imagery experiments and therapeutic practice. These single and partly special cases include (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 dislocation of the 5th rib (65 yrs., 185 cm, 86 kg) and (4.) a female participant (33 yrs, 167 cm, 56 kg) with a particularly clear reaction to negative food imagery. In these, the AF of elbow or hip flexors was measured analogously to the experiments described above (3 trials in each state; input measurement, intervention/treatment, output measurement at the same day within ~60 min). Tester B executed the measurements in cases (1.) to (3.), tester A in case (4.). In cases (1.) to (3.), the participants already showed unstable muscles in entry state. They regained their stability after specific interventions [(1.) positive imagery of exercising Yoga or a victory in

kickboxing, (2.) individualized pulsed electromagnetic field (PEMF) applied to the ankle, (3.) manual mobilization of the rip in posterior direction and PEMF to the rip].

Figure 7 illustrates examples of force and gyrometer signals from the AF measurements for each case and the M and SD for the three trials each. First, it should be noted that the force increases were similar for all stable and unstable muscle tests (Figures 7A-D). This mirrors the reproducibility of the testers' force profiles.

For cases (1.) and (2.) stable and unstable muscles behaved similarly compared to the overall group described above. The AF_{max} for stable and unstable trials was at a considerably high level, while the $AFiso_{max}$ revealed clearly lower values for unstable vs. stable (Figure 7A, B). This resulted in ratios $\frac{AFiso_{max}}{AF_{max}}$ of 44% and 63%, respectively (Figure 7E). The oscillations (AFosc) in unstable muscles occurred after the breaking point ($AFiso_{max}$), in stable muscles they arose clearly below that force level.

For case (3.) the main difference was that AF_{max} for the unstable state was clearly lower than for the stable one (~145 vs. 233 N, Figure 7C, E). It must be pointed out that the output measurements (stable conditions) were performed directly after the treatment. This indicates that the patient was not able to generate his maximum force as long as the obviously impairing stimulus of rib dislocation was present — even not during muscle lengthening. Once this stimulus was removed by treatment, he was able to acquire his maximum force in holding muscle function under static conditions. Despite this phenomenon (even low AF_{max} for unstable trials), the ratio $\frac{AFiso_{max}}{AF_{max}}$ was 70% for unstable and 100% for stable muscles — similar to the overall group. This occurred since the $AFiso_{max}$ was particularly low in the unstable state, with an average of 105 N. Noticeably, no oscillations emerged during the force increase in unstable trials, while they occurred at ~50% of AF_{max} in stable trials (Figure 7C, E).

A similar but even clearer pattern is seen in case (4.) (Figure 7D). As AF_{max} was at a considerably high level in stable trials (~196 N), the participant was unable to generate this force during negative imagery, even in the eccentric phase, and overall, only reached 35% of her maximum force under stable conditions/positive imagery (~68 N). This reflects that the muscle not only gave way but literally collapsed shortly after the tester's force increase began. Since the muscle started to lengthen at an even lower force (~54 N), the ratio $\frac{AFiso_{max}}{AF_{max}}$ amounted still only ~77%. Although this was the highest value in the comparison of the four single cases, the trials of case (4.) showed the clearest reaction in response to the negative imagery mirrored not only by $AFiso_{max}$ but also by AF_{max} (Figures 7D, E).

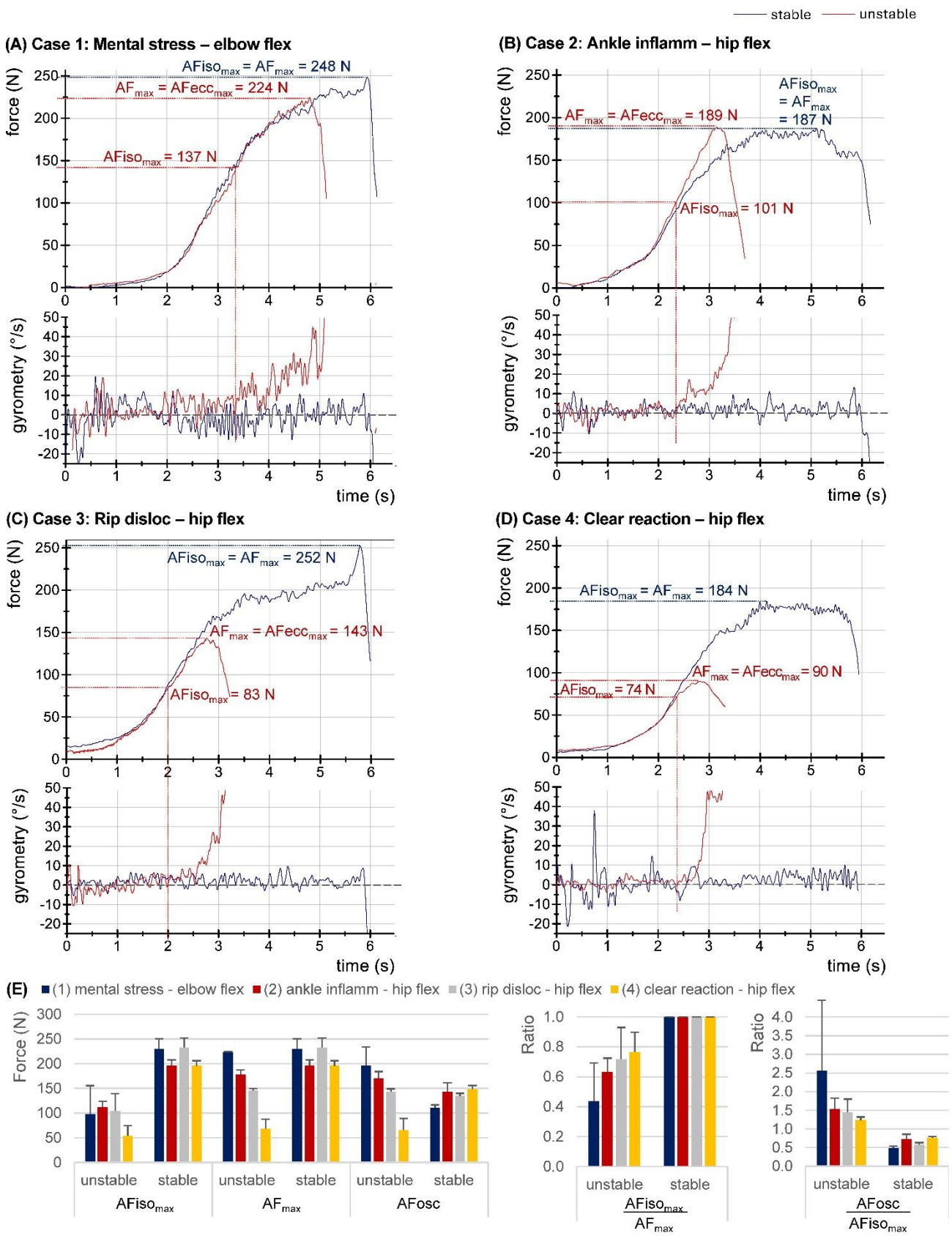

Figure 7. Single cases.
*(**A**) to (**D**): Force and gyrometer signals during AF measurements (blue: stable, red: unstable) of (**A**) case 1: elbow flexors of a female student with current stress vs. positive imagery; (**B**) case 2: hip flexors of a male patient with acute*

*ankle inflammation vs. post-treatment after pulsed electromagnetic field (PEMF); (**C**) case 3: hip flexors of a male patient with rib dislocation vs. post-treatment after manual mobilization and PEMF; (**D**) case 4: hip flexors of a female person during negative vs. positive food imagery showing a particularly strong reaction with negative imagery. The values of max. isometric AF ($AFiso_{max}$) and max. AF (AF_{max}) are marked. In case AF_{max} was reached during muscle lengthening, the term $AFecc_{max}$ was used indicating eccentric muscle action.*
*(**E**) Arithmetic means and standard deviations of the three trials of each case for the $AFiso_{max}$, AF_{max}, AFosc (all in N) and their ratios. The values are categorized in stable and unstable muscles.*

4 Discussion

Muscle stability in the sense of the adaptive holding capacity is overlooked in sports, movement and health sciences or medicine until now. Muscle strength or other aspects of muscle function (mainly electromyographic activity), assessed during pushing muscle actions, are the parameters of interest in science and clinical assessments. Holding and adaptive components are largely ignored and their relevance underestimated. Research in recent years underpin that PIMA and HIMA are to be distinguished whereby HIMA requires more complex control processes (20). It is plausible that the neuromuscular system is even more challenged if a person needs to adapt to varying external loads—a function which is frequently required in everyday life and sports. It can be assessed by measuring the Adaptive Force. Our research group focused on this special muscle function in the past years which resulted in six experimental studies on muscle stability under different conditionings. This article synthesized and evaluated the results of those experiments with the aim to characterize muscle stability, to identify the essential characteristics of stable and unstable adaptation, to discuss its relevance and to provide suggestions for future studies and clinical applications.

The most important findings are that the relative AF parameters are independent of the investigated factors and that muscles can instantly switch between stability and instability depending on internal or external stimuli. The practical relevance of this phenomenon is discussed below. First, muscle stability is characterized based on the results found.

4.1 Characterization of muscle stability: stable vs. unstable

Muscle stability is defined here as the capacity to resist and adapt to external loads. Different parameters of Adaptive Force are used to objectify muscle stability. The findings indicate that basically two characterizations can be distinguished: stable and unstable muscles. The results provided some key points for the objectification of muscle stability:

(1) Stable muscles are characterized by the ability to reach their maximum strength under static conditions while adapting to an increasing external load (adaptive holding isometric muscle action). That means the parameter $AFiso_{max}$ is approximately equal to the peak force AF_{max} (~99.4 ± 1.8% of AF_{max}). In contrast, unstable muscles cannot achieve their maximum strength under static conditions when an external force is impacting, i.e., they begin to lengthen at clear submaximal intensities, reflecting a significantly reduced maximal holding capacity ($AFiso_{max} < AF_{max}$; averagely ~55.8 ± 16.0% of AF_{max}). What is important here is that unstable muscles usually still reach their maximum strength, but only during muscle lengthening. That means, the static position is already left before reaching the peak force. This is in clear contrast to stable muscles, which are able to access their maximum strength under static conditions. Hence, the relative holding capacity $\frac{AFiso_{max}}{AF_{max}}$ is the parameter that best reflects muscular stability or instability, respectively. It should be used to assess and distinguish stable vs. unstable muscles. As this is independent of the assessed muscles, testers, participants' sex, and the conditioning this outcome seems to characterize a general phenomenon, at least for the test settings used in the related studies.

(2) When muscles are stable, distinct mechanical oscillations occur at submaximal intensities (~75.0 ± 10.8% of AF_{max}). Unstable muscle tests, in contrast, are characterized by an almost complete absence of oscillations (~91.4 ± 9.8% of AF_{max}). It has already been shown that two neuromuscular systems develop common oscillations in a synchronous rhythm during isometric muscular interaction at submaximal intensities (27–30). When adapting to an increasing external force, such as AF, the occurrence of oscillations could be a fundamental factor in creating muscle stability in a dynamic oscillating manner. Apparently, despite two persons are involved, the onset of oscillations seems to depend on the person being tested, which must adapt to the force increase in a holding way. In case the participant is affected by an interfering stimulus the upswing to joint synchronized oscillations seems to be failing. The onset of distinct oscillations could therefore be a sign or even a prerequisite for muscular stability.

Table 3 summarizes some key aspects of the characterization of stable and unstable muscles compared to the common pushing maximal voluntary isometric contraction (MVIC).

Table 3. *Key aspects characterizing stable and unstable muscles compared to the common pushing isometric maximum strength.*

Parameter	Muscle stability (adaptive max. HIMA)	MVIC (max. PIMA)
Assessment	• resisting an external load • adapting during holding action	• pushing against resistance • no adaptation
Sensitivity in reaction to stimuli	High and immediate	low
Parameters	• AF_{max} = peak force • $AFiso_{max}$ = max. HIMA • AFosc = force at onset of oscillations • relative parameters	• F_{max} = peak force (max. PIMA) • - • amplitude/frequency of oscillations • -

4.2 Factors influencing the parameters of muscle stability

A distinction must be made between factors that can influence the AF parameters due to the test constellation (e.g., sex and physical condition of tester and participant, force increase, positioning, reproducibility etc.) and those that can affect muscle stability from a physiological point of view (i.e., affecting stimuli). The latter will be considered below.

Regarding the former, a few basic physical principles should first be pointed out. The force measured during manual muscle testing must always be generated by both parties simultaneously. It therefore reflects their combined performance. The tester must adjust the force applied to the participant's capabilities and biomechanical requirements of the muscle. For example, when testing a female person, a small muscle, or with a long lever, less force is usually required than when testing a male person, a large muscle, or with a short lever.

Some of these factors were included in the statistical analysis presented. The only factor that influenced the absolute AF parameters was the tester (female/male). The maximum holding capacity ($AFiso_{max}$), peak force (AF_{max}) and the force at onset of oscillations (AFosc) were significantly lower for the female than for the male tester. For $AFiso_{max}$ and AF_{max} this can be presumably led back to conditional aspects. Females have less maximum strength than males (31). For AFosc sensorimotor control and kinesthesia might be more relevant than maximum strength. Sex- and age-differences in somatosensation and sensorimotor function are known (32,33); however, discussing them here would

go beyond the scope, especially since the sample consists of only one middle-aged female and one older male tester. Obviously, in case the female tester assessed the AF, the oscillations started on a considerably low level of force (Figure 4B). This could reflect a higher sensitivity of the female tester, which could lead to stability being perceived even at lower intensities. Accordingly, this tester could have stopped the application of force at a lower level, as she already perceived the muscle as stable. However, this might be an individual phenomenon. Most important is that the relative AF parameters ($\frac{AFiso_{max}}{AF_{max}}$ and $\frac{AFosc}{AFiso_{max}}$) were neither influenced by the tester (and thus presumably their sex or conditional aspects) nor by the participants' sex.

The different muscle groups showed a similar pattern for stable and unstable state. Solely the pectoralis major revealed a relatively higher $AFiso_{max}$ (Figure 5). Despite the small number of pectoralis muscles (n = 3), a peculiarity of its setting should be mentioned as possible reason. The pectoralis muscle was tested with a long lever at the distal forearm. This resulted in more pronounced oscillations during the test which were visible in the gyrometer signal. Since the evaluation of $AFiso_{max}$ is based on the zero-line crossing of the gyrometer signal, the stronger oscillations shifted the curve's lift-off over the zero line to a later timepoint and, thus, to higher force values. For further investigations it should be explored whether a different data processing method (e.g., stronger filtering) might be more suitable for muscles with a long lever and stronger oscillations, or whether different threshold values need to be defined for different muscles.

The between-subject effects regarding the factor 'experiment' are presumably related to the constellation of tester and participant. Since the male tester performed the AF assessment in both spindle experiments on predominantly male athletic participants, the higher AF_{max} and AFosc values are obvious. It is noticeable that the absolute AF parameters of the study 'spindle-manipulation' are higher compared to all other experiments (Figure 4D). Since the participants were exclusively young, well-trained soccer players, it is very likely that this constellation of examiner and participants can be considered the cause. Therefore, the high absolute AF values in these experiments should be interpreted with caution. However, the relative AF parameters again were not affected by this.

Although not significant, it is worth mentioning that only in the 'Long COVID' experiment the AF_{max} value on average was lower in the unstable state than in the stable state (mean difference = 6.4 N, Figure 6). In all other experiments, the AF_{max} was on average greater in the unstable state, albeit in the 'spindle-procedure' experiment the difference was minor (~3,5 N) and not significant (Figure 6). Since muscles can reach their highest forces during lengthening (34), the effect of higher AF_{max} in the unstable state is not surprising—these were achieved during the eccentric phase. The absence of this effect in long COVID patients could indicate that in such a state, the achievement of maximum forces is generally limited—not just the maximum holding capacity. For the 'spindle-procedure' experiment, we can only guess why the AF_{max} in the unstable state was only slightly higher than in the stable state. It is conceivable that the force values were already close to the muscles' maximum force capacity in the stable state (indicated by ~2% higher force values at AF_{max} in stable state compared to MVIC; for comparison: in the spindle experiment, these were 3% lower). Another possibility is that the special preconditioning (contraction at maximum muscle length) also affected the capacity to generate the maximum strength—even during muscle lengthening. Further experiments would have to investigate this.

In summary, with regard to practical application, it is essential that (1.) possible influencing factors on the absolute AF parameters, such as the tester, are irrelevant as long as the tests are carried out by the same person and setting in both conditions—stable and unstable—and (2.) that the relative AF parameters are independent of such factors. This allows for comparison between different studies.

The independence of the main parameter $\frac{\mathrm{AFiso_{max}}}{\mathrm{AF_{max}}}$ from all factors considered eliminates the need for reference tables and makes the test a robust and universally applicable marker in diagnostic settings.

4.3 Practical relevance of muscle stability

As mentioned above, the causes of the development of musculoskeletal complaints or non-contact injuries are still not fully understood despite decades of research. Questions remain unanswered, such as: How do complaints arise when there is no corresponding structural correlate (35–37)? How can the correlation between mental stress and musculoskeletal complaints be explained (38–40)? Why do complaints only arise on one side despite equal strain on both sides? Why do they often only occur in a minority of athletes (41)? Why do well-trained athletes develop complaints or non-contact injuries at all, often during movements that require normal exertion and that they have performed thousands of times before (42,43)? Results on maximum strength and neuromuscular imbalances are inconclusive and the theoretical basis is lacking (9) The often-cited 'overload' cannot be the decisive factor here either (see below). There must be intrinsic. factors that affect neuromuscular control in such a way that the holding and braking muscle action is limited when forces are exerted. The target parameters considered to date may not be suitable for this purpose. The novel approach of AF assessment is a promising solution which could unravel the open questions regarding non-contact injuries and musculoskeletal complaints.

The special characteristics of muscle stability substantiate this: (1.) The assessment of AF includes the adaptive component which is not taken into account in common measurements of maximum strength; and (2.) the high sensitivity of the holding function ($\mathrm{AFiso_{max}}$) including its immediate response to interfering stimuli. When a disruptive stimulus interferes with the highly demanding motor control required for holding and braking activities, the holding capacity ($\mathrm{AFiso_{max}}$) can be reduced substantially—even in healthy individuals, as has been shown. This reaction must be reflexive in nature and could explain complaints and non-contact injuries under normal strain, as well as sudden non-contact injuries—which occur during a single movement that was previously performed countless times without any problems.

The capacity to resist and adapt to external loads is frequently required in everyday life and in sporting activities. We need stability when forces act upon us. These include the ground reaction forces generated by gravity such as landing. Stability is also required to compensate for the inertial forces that arise in our body when we slow down movement. Adaptive Force is also required to compensate for centrifugal forces during rotational motions. In other words: stability is necessary when we walk downstairs, run or change direction, because all cyclical movements consist half of acceleration and half of deceleration. The higher the braking activity, the higher the demands on the regulation of stability. Based on the required kinesthetic information, the sensorimotor system must ensure that the muscle lengths specified in the movement program are maintained during the holding and braking action, while at the same time providing a force response that meets the requirements. The data currently available suggest that instability occurs when the interplay between length and tension regulation is disturbed. Unstable muscles are not weak, because they develop their full maximum strength during the yielding process. However, above a certain force level, the system appears to be unable to readjust length and tension adequately. The target muscle becomes the weakest link within the closed kinetic chain, causing it to yield early in the force increase. It is reasonable to assume that such behavior impairs the stability of joints, including their connective tissue structures. Such a mechanism could also explain the altered lower limb biomechanics observed in individuals prior to injury during jump-landing tasks (7). The following examples are intended to illustrate possible resulting mechanisms: Imagine a running person's foot is firmly on the ground and

they want to change direction. In doing so, it is imperative that the knee muscles stabilize the joint components; the passive structures are not designed to fully absorb the forces that occur. If the muscles lengthen prematurely at submaximal forces, the joint components could be forced to twist too much at an early stage under the influence of the body's own rotational inertial forces. The load on the passive structures could become excessive. It is plausible that injuries may occur as a result. Something similar happens when walking on uneven ground. The foot muscles have to adapt to these uneven surfaces in order to compensate for them. If this does not work properly, the ankle could twist. Such a mechanism is assumed for all activities in which forces must be absorbed. Even with purely holding isometric muscle activity (static), such as dorsal extension of the wrist while working at a computer, a reduced holding capacity could lead to joint instability. Prolonged activation under these conditions may result in inadequate strain of muscle insertion and ultimately to pain (e.g., tendinopathy). The basic principle of the examples given is that functionally induced muscle instability can expose joints to increased stress. This could result in reduced resilience, discomfort or even injury. We therefore refer to this phenomenon as functional instability syndrome (FIS). For the time being, FIS remains a hypothetical construct. However, it is based on the basic research mentioned above and on many years of practical experience in the diagnosis and treatment of musculoskeletal complaints. The next steps should involve clinical studies. If they support the FIS thesis, it appears imperative to incorporate holding actions including adaptive components into the examination of muscle function to identify potential limitations. Since the essence of pushing or pulling muscle actions (e.g., MVIC) is to act rather than react, methods such as MVIC measurement are only suitable for assessing muscle strength, but not muscle stability, which could be more important in the context of complaints and injuries. Further scientific substantiation provided, a paradigm shift should be initiated, moving the focus from muscle strength to muscle stability.

4.3.1 Muscle stability and non-contact injuries

The majority of sports injuries occur without external contact (44–46). The conditions under which non-contact injuries occur have been studied and known for a long time, but have not yet provided a plausible explanation for the development of injuries (8,44,45,47–49). Running, twisting/turning, landing and deceleration being the main activities in which non-contact injuries occur (8,44,49,50). Several risk factors associated with injuries have been discussed such as playing position and situation (50,51), anatomical factors as postural alignment, joint angles, hypermobility etc. (49,51), sex, hormone concentration and menstrual cycle (51,52), neuromuscular factors as muscle strength, muscle activation patterns, muscle stiffness, functional asymmetries and muscle fatigue (6,8,51,52), injury history, genetics and other demographic factors (51,52), as well as biomechanical ones such as the load on the anterior cruciate ligament (ACL) (53). Explanations for biomechanical correlations are only based on various hypotheses so far and thus, remain still unclear (49). Hypothesized for ACL-injuries were substantial stress on the ACL, increases of the compressive vector within the knee, interaction of thigh and lower leg muscles, degree of knee flexion and foot positioning (54–56). Despite this extensive research, it has not yet been possible to identify a common denominator for non-contact injuries and it is unlikely that one denominator will be found because every person is an individual and numerous different intrinsic and extrinsic factors work and influence the individual.

It is recommended to focus on the muscle function in which non-contact injuries usually occur: muscle lengthening under load, when a muscle must hold or decelerate an external load (1,3–5). The common strength assessment (MVIC, i.e. PIMA) does not include this aspect of muscle function. This could, however, explain the lack of significant differences in strength between injured and non-injured athletes (50). The assessment of muscle function should include the adaptive component, as in the measurement of AF. The special characteristics of muscle stability might also explain why

non-contact injuries occur even when the strain is not exceptionally high and the motion has often been performed before without injury: as the presented studies showed, the $AFiso_{max}$ reacts sensitively and immediately with a substantial reduction in the case of various interfering influences such as negative emotions, proprioceptive or nociceptive stimuli. Based on our own experience in caring for athletes, we strongly suspect that nociception could play a prominent role here. Apart from the case study presented above, which supports this assumption, no corresponding research has been conducted to date. There is an urgent need here.

The reported higher injury rate in women compared to men (51) could also be explained by the approach of muscle stability. In the present analysis, females demonstrated a lower ratio $\frac{AFiso_{max}}{AF_{max}}$ in unstable muscles compared to males indicating that women may be more sensitive to the applied disturbing stimuli. From our own practical experience with patients, we know that hormonal changes can affect the holding capacity, too.

Since most of these negative stimuli cannot be eliminated through training, it is postulated that muscle stability in the sense of AF is not trainable per se. This is because the decline in holding capacity is very likely reflexive in nature. Provided there are no destabilizing influences, i.e. the muscles are fully stable, training the holding and braking function, could make a valuable additional contribution. Thus, the capacity to hold in reaction to varying external forces could be optimized through specific exercise interventions, which in turn could contribute to injury prevention. This is supported by studies showing that eccentric exercise programs reduce the injury rate, e.g., in hamstring strain injuries (57–60) with some limitations (61). The Nordic hamstrings exercise ultimately involves aspects of the AF, as you have to resist an increasing external load. The positive effects of this kind of exercise could be an indication that such training can optimize muscle stability resulting in a reduction of injuries. Given the reflexive nature of the holding capacity, the following two aspects should be taken into account for injury prevention: first, the elimination of possible interfering influences at the reflexive level and second, good stabilization training.

4.3.2 Muscle stability and musculoskeletal complaints

Musculoskeletal complaints have a high prevalence in normal population with enormous social and economic costs (62). For example, low back pain remains the leading cause of the number of years spent living with a disability in 2019, with women being affected more frequently and the number of people affected increasing with age (62). Factors such as hormonal differences and intervertebral disc degeneration are reported regarding sex-differences and age, respectively (62). Also in athletes the prevalence is high, e.g., in basketball with 43% for back pain and 36% for neck pain (63). Risk factors such as postural changes or deviating spinal curvature/spinal imbalances (43,63) as well as sex differences (51) were reported. However, it remains with the description of risk factors. Causes cannot be identified. Orthopedic complaints are also often associated with ‘overuse’, in the context of sports called ‘overuse-injury’. The fundamental question is whether these are truly attributable to ‘overuse’. If this is indeed the case, it raises the question of how, for example, Achilles tendon complaints can develop on one side despite equivalent loading of both limbs. Another fact is that most athletes do not develop so-called overuse injuries despite being exposed to the same load. For instance, the incidence rate among runners who run middle to marathon distance regarding running-related musculoskeletal injuries (RRMIs) ranges from 4.0% for stress fracture, 5.1% for iliotibial band syndrome, 6.1% for plantar fasciitis, 6.3% for patellofemoral syndrome, 9.4% for medial tibial stress syndrome and up to 10.3% for Achilles tendinopathy (41). That means the vast majority of athletes do not develop those RRMIs under equal loading conditions. The term ‘overuse-injury’ suggests causality. If this were the case, it would be expected that at least a substantial majority of

athletes would be affected. Load is certainly a factor, but there must also be intrinsic factors related to loadability. In the case of insufficient resilience, a correlation of complaints and load would be reasonable.

It would be worth considering which factors might contribute to a decrease in resilience. Given the sensitivity of muscle stability to various stimuli, it is conceivable that the related muscles may exhibit instability due to an impairing stressor. In our clinical practice, the presence of unstable muscles related to affected structures is a common observation. The case examples described above should illustrate this. The patients with acute ankle inflammation (case 2) and rib dislocation (case 3) showed instability of the hip flexors reaching averagely a holding capacity of 63% and 72% of AF_{max}, respectively. It is assumed the nociception led to the reduced $AFiso_{max}$; apparently not only in the muscles directly located at the affected area. It was striking that in the patient with rib dislocation (case 3), even the AF_{max} in the unstable state was clearly lower than the AF_{max} in the stable state (amounted to only 62%). This is probably due to the fact that the affected 5th rib is involved in the force transmission chain for stabilization during the test. Performing the test could therefore have been disrupted the 5th rib as an additional challenge, which could explain the rather unusual drop in AF_{max} (usually only $AFiso_{max}$ reacts clearly). This also means that the holding capacity ($AFiso_{max}$) in the disturbed state (unstable) was only 45% of the maximum force values (AF_{max} and $AFiso_{max}$) that the hip flexor could generate in the undisturbed state (all measurements were done within 1 h). However, apparently, there are also individuals in whom such a severe reduction in maximum force can occur without any effect on the force transmission chain, as shown by case 4. The mere imagination of a disgusting food led to a 65% reduction in AF_{max} and 73% in $AFiso_{max}$ compared to the AF_{max} value reached during positive food imagination (ratios $AF_{max_unstable}$ to AF_{max_stable} = 35%; $AFiso_{max_unstable}$ to AF_{max_stable} = 27%). On the one hand, this demonstrates the immense power of emotional stimuli, and on the other hand, it indicates personal differences in regulatory capacity or sensitivity regarding disruptive stimuli. Obviously, there are individuals who react particularly strongly—also with regard to neuromuscular control. Such strong reactions are considered rather unusual. However, also in case 1 (healthy participant with acute mental distress due to an upcoming exam), the $AFiso_{max}$ was below 55% of AF_{max}. Both individuals with the clear reaction to emotional imaginations were female. It is assumed that females generally react more sensitively than males. This may represent another possible explanation for the higher susceptibility to injuries in women, although further verification is required.

We postulate that a substantially reduced holding capacity could be of great importance for the development of injuries and complaints. The above explanations of the suspected underlying mechanisms provide at least a plausible theoretical basis. As individual factors and the individual's regulatory capacity influence the holding capacity in general and the extent of reduction in particular, it is recommended to focus on the individual resilience rather than the load.

4.3.3 The potential of muscle stability for deriving therapeutic measures

In the context of therapeutic approaches, the individual interfering factors also mean that the cause of reduced resilience must be identified on an individual basis—this applies also for injury prevention. As has been shown, even healthy individuals exhibit a reduction in their holding capacity in the presence of disruptive stimuli. This highlights the high sensitivity and, above all, the early response of this muscle function to existing disruptive factors; this can and should be used. It is important to note that the possibility to detect immediate changes in muscle stability enables the identification of both disruptive factors and positive influences. Not only the holding capacity reacts with instability to impairing stimuli, but unstable muscles respond instantaneously to supportive stimuli as shown in the studies and single cases presented (14,16–19,21). This allows individually supportive measures to

be identified on the basis of muscle stability and therapies derived from them. The procedure was described in the case report of one Long COVID patient (18). This approach is highly personalized, with a focus on identifying and addressing the underlying individual causes of the condition. It could therefore be more targeted, tailored to the individual. Our clinical practice experience is very promising, but clinical studies are needed to verify the effects.

4.4 Limitations and methodological aspects

Limitations of the underlying studies are not addressed here, as they are discussed in the respective articles. Data from previous studies was used for the present analysis and pre-sorted into 'stable' and 'unstable' muscles. The aim was to compile all available data on muscle stability and thus potentially define fundamental common characteristics of stable and unstable muscles. In this regard, pre-sorting was deemed permissible. However, this is also the reason why the results do not indicate how the muscles responded to different stimuli (this analysis can be found in the underlying articles). It should be briefly noted that across all studies, the muscles reacted in accordance with the hypotheses in 97% of cases [stability with supportive intervention/baseline: 98.8% (475 of 488 trials); instability with disruptive intervention: 94.5% (290 of 307 trials)].

The statistical analysis showed that the factor 'tester' was the only one that had an influence on the AF parameters, and only on the absolute ones. Due to the special tester-participant constellation, a design artifact can be suspected here. The male tester conducted all tests in both spindle experiments, in which predominantly athletic male participants were measured. Accordingly, higher values can be assumed. Even if a lower maximum strength can also be assumed for female vs. male testers, the testers' maximum strength is considered subordinate due to the test setting: the testers can use their entire body, while the participant's muscles are largely isolated. Future studies should examine tester specific influences (sex, age, experience, physical condition) considering a larger number of testers.

When comparing the different muscles, the descriptive analysis revealed higher $AFiso_{max}$ values for the pectoralis muscle, which led to a higher ratio $\frac{AFiso_{max}}{AF_{max}}$. It is assumed that the lack of significance is due to the small sample size (n = 3 pectoralis muscles). Due to the specificity of the data evaluation, which uses the zero crossing of the gyrometer signal as a reference for the breaking point, the stronger oscillations during the pectoralis test probably led to the higher $AFiso_{max}$ values purely on the basis of the evaluation method (for details see discussion above). Further studies should include a larger number of each muscle, as well as other muscles, and investigate possible refinements to the data analysis with regard to strong oscillations, which can also occur in other muscles.

Finally, reference should also be made to the selective group of participants for the spindle experiments. Future research should investigate the effects of supportive and disruptive stimuli on a variety of participants and also investigate other stimuli that may affect the holding capacity.

5 Summary and Conclusion

Stable and unstable muscles can be clearly distinguished by different absolute and relative AF parameters. Overall, unstable muscles showed a dramatically reduced maximum isometric holding capacity of only 56% of their maximum strength. Paradoxically, in the same test during the eccentric yielding the strength increased to values that were mostly higher than under stable conditions. Thus, the muscles were not weak, but unstable. They gave way at clearly submaximal levels.

Under stable conditions, the sensorimotor systems of tester and participant synchronized to a common oscillation (recorded dynamometrically and kinematically), thus were able to coordinate with each other. This phenomenon was hardly or not at all visible in cases of instability. This suggests (1.) that interactive stability between two partners is not really static but a dynamically oscillating equilibrium and (2.) that it could be a prerequisite of generating stability. It is assumed that the joint closed kinetic chain formed by the two becomes unstable if one system involved cannot coordinate well with the other. As this was the case when disturbing influences were affecting the participant tested, the holding task is considered especially sensitive regarding interfering influences.

It is assumed that early yielding under increasing load destabilizes joints, especially if the muscles concerned are supposed to perform a stabilizing function. For this mechanism, the term functional instability syndrome (FIS) is proposed. It may represent a significant factor in the development of injuries and so-called overuse syndromes. This mechanism reflects a genuine reduction in loadability. Against this background, it appears plausible that higher and particularly intensive eccentric loads lead to an increased incidence of injuries or complaints, as is the case in reality. This would explain the correlation with load, which would then only be a cofactor.

The above hypothesis of instability as a risk factor for injuries and complaints urgently needs to be underpinned by studies. The consideration of Adaptive Force could also play a predictive role in the rehabilitation after surgery or conservative treatment, also regarding aspects of ‘return-to-sports’, which would have to be demonstrated in studies.

In case the presented results would be verified by sufficient further research they would challenge the following two currently prevailing paradigms: (1) The strength paradigm: it has not really been proven. We recommend shifting the focus away from strength and towards stability. (2) The overuse paradigm: we recommend a shift to the resilience paradigm. AF could play an important role in this.

The muscles changed their state between ‘stable’ and ‘unstable’ immediately under the influence of disturbing or helping stimuli. This property could make them a valuable tool for personalized diagnostics. The potential here is enormous and affects a wide range of possible applications. We recommend introducing a standardized and valid testing procedure for muscle stability. The device-based objective manual muscle test of Adaptive Force presented here is very well suited for this purpose. The relative maximum holding force has proven to be very robust, as it is not influenced by very different subject populations or testers. This makes it independent of performance-, sex- and age-related reference values. These are characteristics that make a measurement method the gold standard. Nevertheless, it should be noted that these statements are still insufficiently supported by research. Further studies with a larger number and distinct groups of participants are required to finally validate the test procedure scientifically.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

LVS: Writing – original draft, review & editing, Conceptualization, Methodology, Formal Analysis, Visualization, Project administration; FNB: Writing – review & editing, Conceptualization, Project administration.

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9 List of Abbreviations

ACL – anterior cruciate ligament

AF – Adaptive Force

$AFiso_{max}$ – maximal isometric Adaptive Force (max. holding capacity)

AF_{max} – maximum Adaptive Force (peak force)

AFosc – AF at onset of oscillations

ANOVA – analysis of variance

CI – confidence interval

CV – coefficient of variation

FIS - functional instability syndrome

HIMA – holding isometric muscle action

M – arithmetic mean

MD – mean difference

MMT – manual muscle test

MVIC – maximal voluntary isometric contraction

PIMA – pushing isometric muscle action

RM ANOVA – repeated measures ANOVA

RRMIs – running-related musculoskeletal injuries

SD – standard deviation

SEM – standard error of the mean

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12 Data Availability Statement

The dataset of this study is available upon request to interested researchers.

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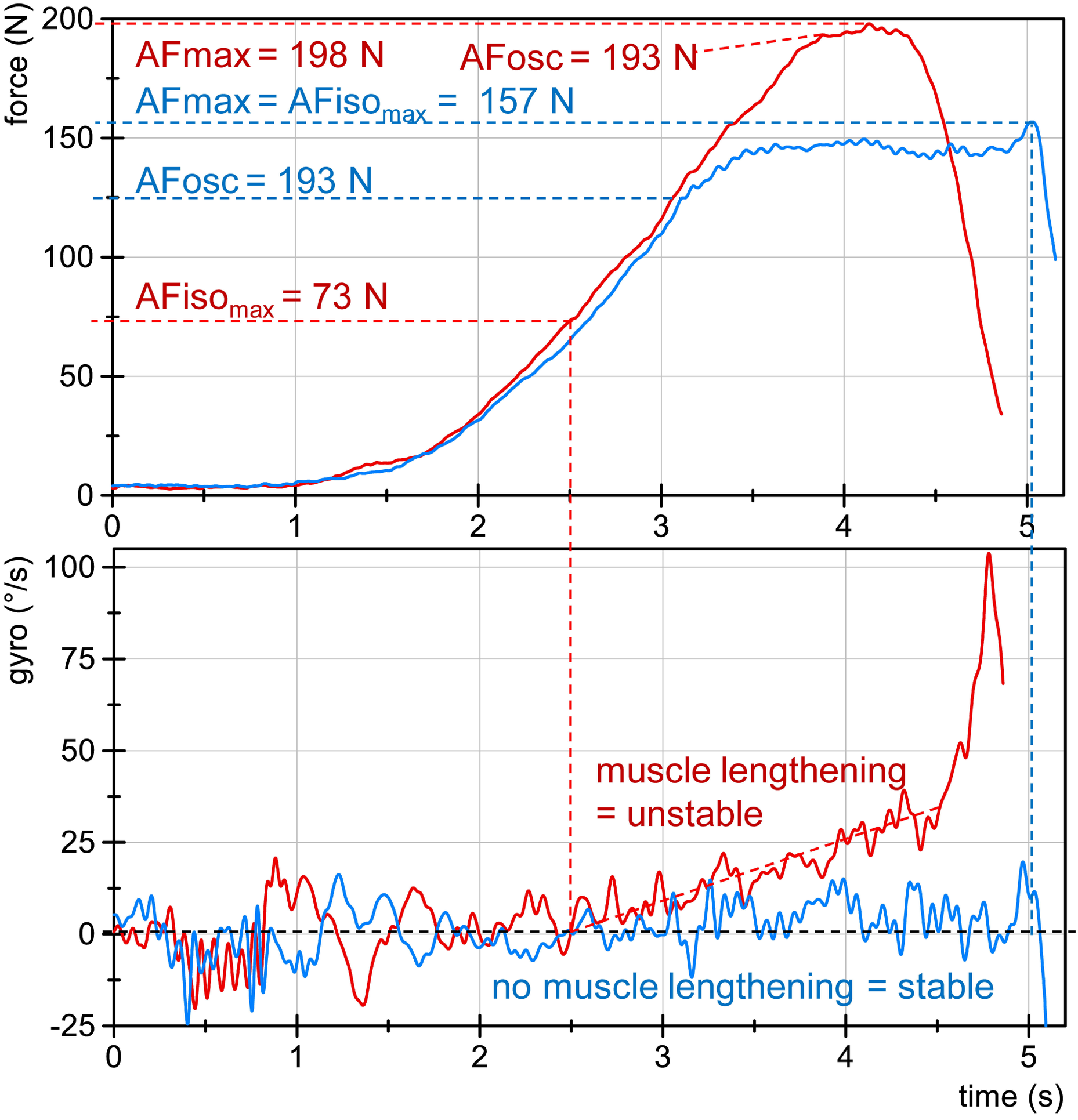
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AFosc = 193 N
AFiso$_{max}$ = 73 N
0
1
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4
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gyro (°/s)
100
75
50
25
0
-25
muscle lengthening
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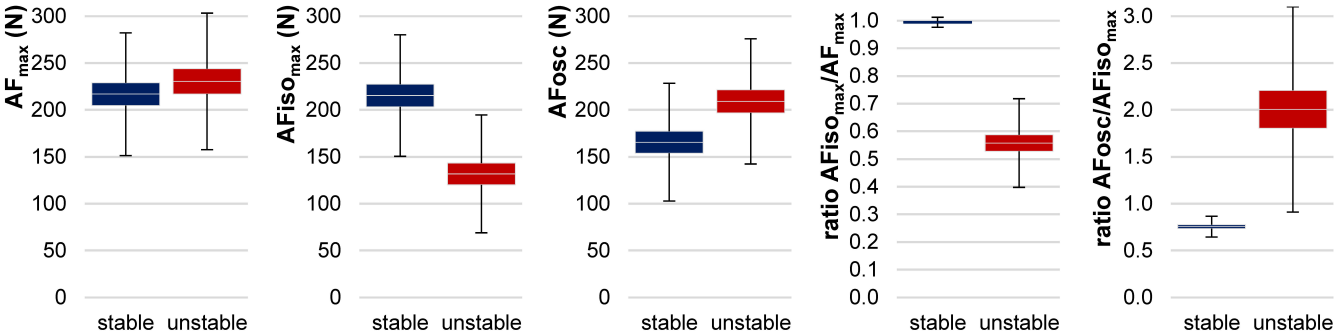
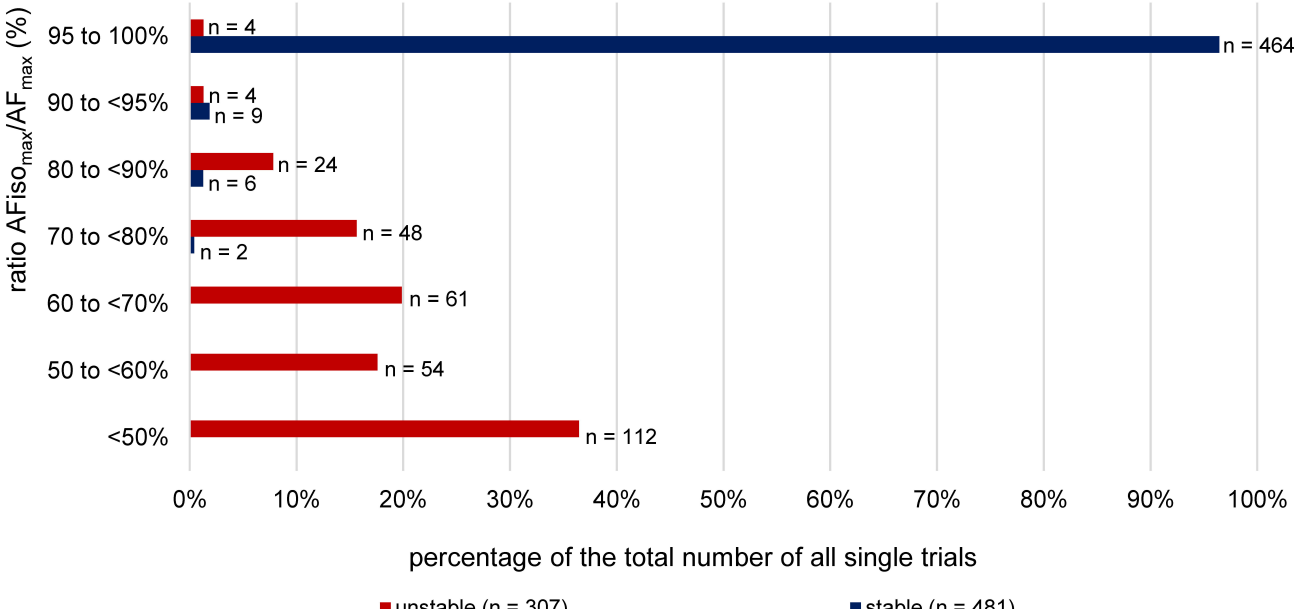
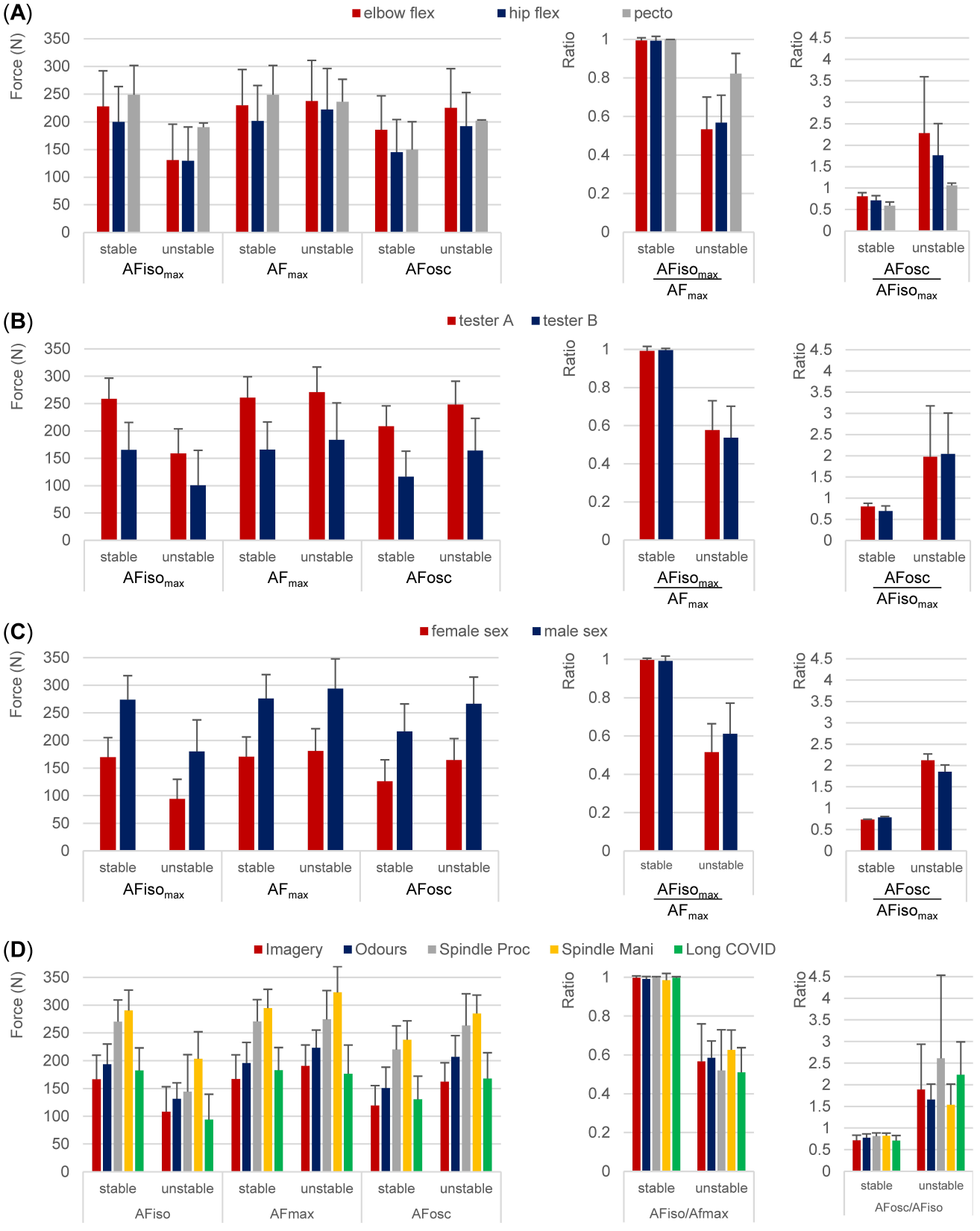
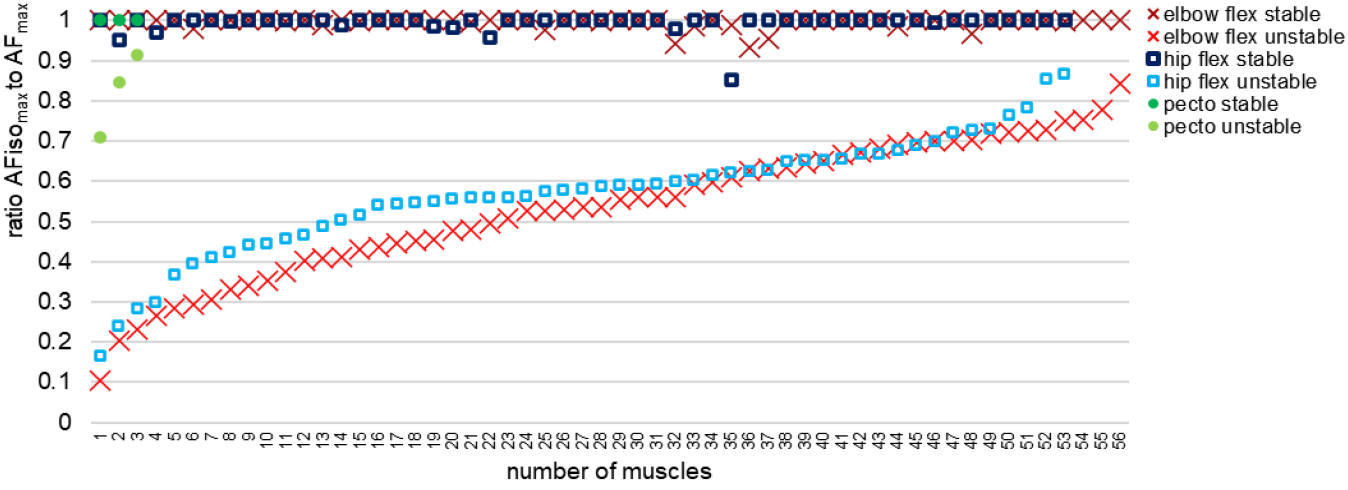
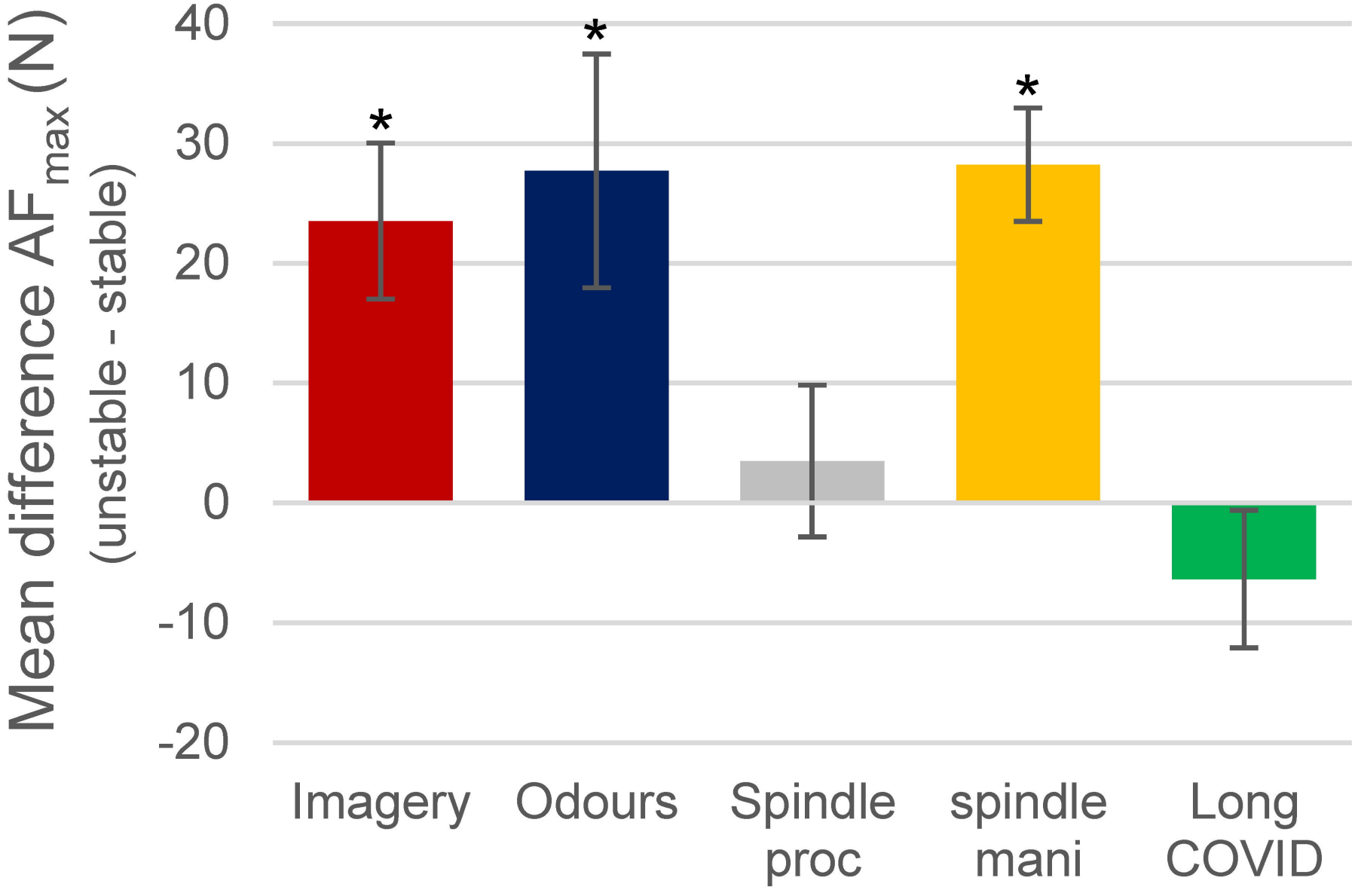
no muscle lengthening = stable
0
1
2
3
4
5
time (s)

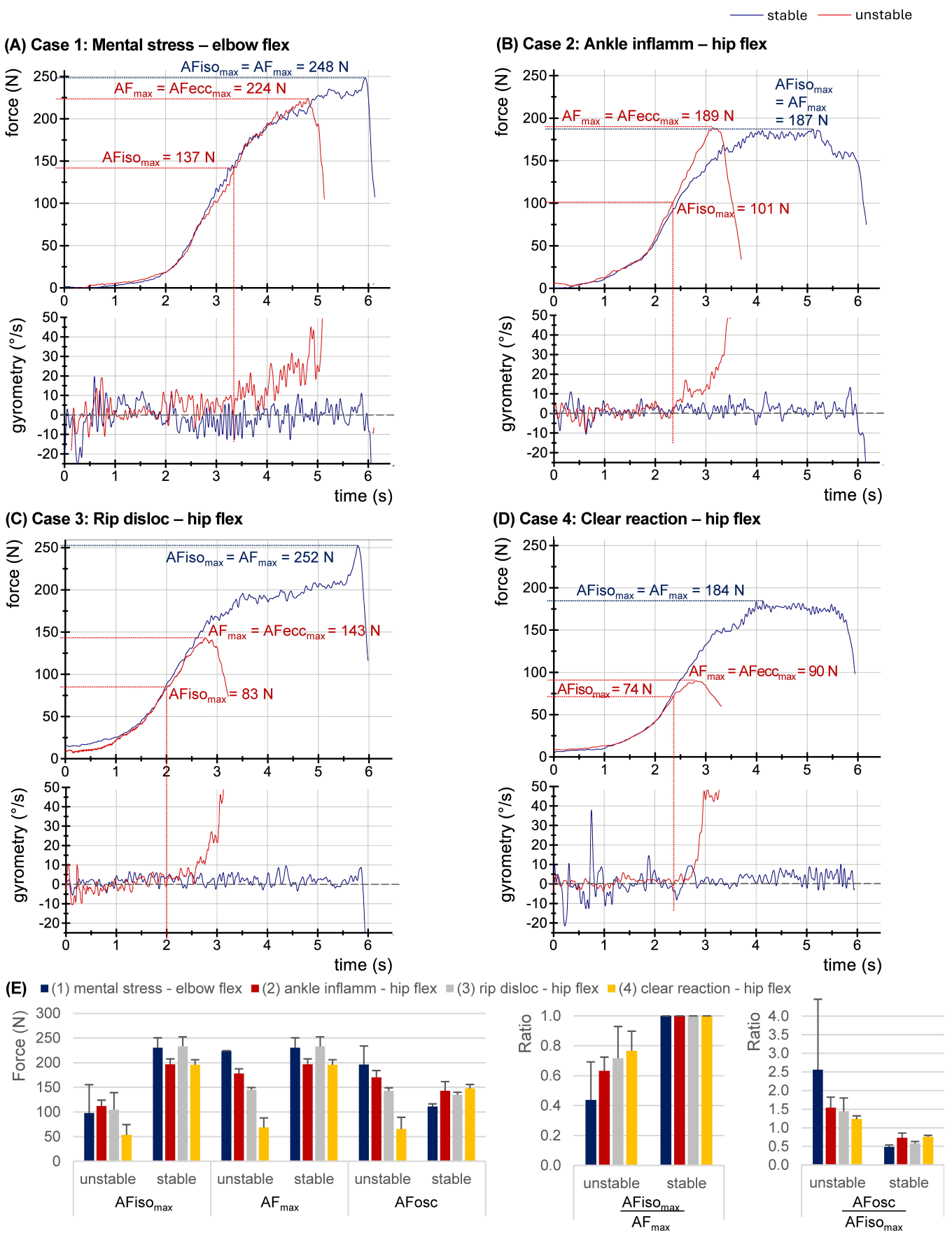

AFmax (N)
300
250
200
150
100
50
0
stable
unstable
(A)
AFisomax (N)
300
250
200
150
100
50
0
stable
unstable
(B)
AFosc (N)
300
250
200
150
100
50
0
stable
unstable
(C)
ratio AFisomax/AFmax
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
stable
unstable
(D)
ratio AFosc/AFisomax
3.0
2.5
2.0
1.5
1.0
0.5
0.0
stable
unstable
(E)


ratio AFiso$_{max}$/AF$_{max}$ (%)
95 to 100%
90 to <95%
80 to <90%
70 to <80%
60 to <70%
50 to <60%
<50%
n = 4
n = 464
n = 4
n = 9
n = 24
n = 6
n = 48
n = 2
n = 61
n = 54
n = 112
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
percentage of the total number of all single trials
unstable (n = 307)
stable (n = 481)


(A)
elbow flex
hip flex
pecto
Force (N)
Ratio
stable
unstable
AFiso$_{max}$
AF$_{max}$
AFosc
AFiso$_{max}$ / AF$_{max}$
AFosc / AFiso$_{max}$
(B)
tester A
tester B
(C)
female sex
male sex
(D)
Imagery
Odours
Spindle Proc
Spindle Mani
Long COVID
AFiso
AFmax
AFosc
AFiso/Afmax
AFosc/AFiso


ratio AFiso$_{max}$ to AF$_{max}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
number of muscles
elbow flex stable
elbow flex unstable
hip flex stable
hip flex unstable
pecto stable
pecto unstable


Mean difference AF_{max} (N)
(unstable - stable)
40
30
20
10
0
-10
-20
*
*
*
Imagery
Odours
Spindle proc
spindle mani
Long COVID


stable
unstable
(A) Case 1: Mental stress – elbow flex
AFiso$_{max}$ = AF$_{max}$ = 248 N
AF$_{max}$ = AFecc$_{max}$ = 224 N
AFiso$_{max}$ = 137 N
(B) Case 2: Ankle inflamm – hip flex
AF$_{max}$ = AFecc$_{max}$ = 189 N
AFiso$_{max}$ = AF$_{max}$ = 187 N
AFiso$_{max}$ = 101 N
(C) Case 3: Rip disloc – hip flex
AFiso$_{max}$ = AF$_{max}$ = 252 N
AF$_{max}$ = AFecc$_{max}$ = 143 N
AFiso$_{max}$ = 83 N
(D) Case 4: Clear reaction – hip flex
AFiso$_{max}$ = AF$_{max}$ = 184 N
AF$_{max}$ = AFecc$_{max}$ = 90 N
AFiso$_{max}$ = 74 N
force (N)
gyrometry (°/s)
time (s)
(E)
(1) mental stress - elbow flex
(2) ankle inflamm - hip flex
(3) rip disloc - hip flex
(4) clear reaction - hip flex
Force (N)
Ratio
unstable
stable
AFiso$_{max}$
AF$_{max}$
AFosc
AFiso$_{max}$ / AF$_{max}$
AFosc / AFiso$_{max}$