 doi:10.20944/preprints202008.0394.v1

Perceptual-cognitive function and unplanned athletic movement task performance: a systematic review

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 doi:10.20944/preprints202008.0394.v1

Abstract

The performance of choice-reaction tasks during athletic movement has been demonstrated to evoke unfavorable lower limb biomechanics. However, the mechanism of this observation is unknown. We conducted a systematic review examining the association between 1) the biomechanical and functional safety of unplanned sports-related movements (e.g. jumps/runs with spontaneously indicated landing leg/cutting direction) and 2) markers of perceptual-cognitive function (PGF). A literature search in three databases (Pubmed, ScienceDirect, Google Scholar) identified five relevant articles. Study quality, rated by means of a modified Downs & Black checklist, was moderate to high (average: 13.5/16 points). Four of five papers, in at least one parameter, found either an association of lower PGF and reduced task safety or significantly reduced task safety in low vs. high PGF performers. Yet, as a) the outcomes, populations and statistical methods of the included trials were highly heterogeneous and b) only two out of five studies had an adequate control condition (pre-planned movement task), evidence was classified as conflicting. In sum, PGF may represent a factor increasing injury risk during unplanned sports-related movements but future research strengthening the evidence of this association is warranted.

Key words: unanticipated, decision-making, brain function, sports, athletes, cognition

 doi:10.20944/preprints202008.0394.v1

Introduction

During the last decades, interactive sports have experienced a variety of changes, in essence becoming faster and more dynamic [1]. Between 1966 and 2010, ball speed in football (soccer) increased by 15 percent while the passing rate rose by 35 percent [2] and in a recent seven-year interval only (2006 to 2012), the number of high-intensity actions per game doubled [1]. An analysis of the average men´s single tennis first serve velocity during the French Open tournament showed a continuous upward trend from 160 km/h in 1991 to 188 km/h in 2009 [3]. These data impressively reflect the grown demands on athletes, which do not only include peripheral factors such as strength and power but also cognitive abilities. To prevent injury and achieve optimal performance, individuals in most sports are required to process a multitude of external (e.g. opponents, teammates, ball) and internal (own position, joint stability) stimuli, constantly adapting the own motor actions within seconds or milliseconds [4]. Against this background, it has been suggested that a variety of skills (e.g. visual scanning, attention, short-term/working memory or inhibitory control), commonly referred to as markers of perceptual-cognitive function (PCF), are paramount for time-constrained decision-making.

Despite the high relevance of PCF in sports, the majority of the applied diagnostic screening methods lack significant cognitive affordances. Frequently, assessments of strength, range of motion or balance rely on controlled, pre-planned single-task movements with limited time pressures, which arguably reduces ecological validity. Indeed, Teramoto et al. [5] found that conventional parameters such as strength or power had no or only small predictive values for game performance in basketball. Even more, the detected variance explanations of motor outcomes were lower than those of non-modifiable length-size variables such has height or wingspan. Similar findings were made by Viscovi et al. [6]. After examining ice hockey players participating in pre-season screenings of the American National Hockey League (NHL), the authors concluded that no single off-ice test was related to on-ice performance.

Researchers have attempted to increase test contextuality and ecological validity by means of combining a typical athletic motor task with a time-constrained decision-making component. Besier et al. [7] instructed their participants to perform straight runs towards a screen, which spontaneously displayed the direction of an immediate cutting maneuver. Interestingly, these unplanned side cuts were associated with unfavorable knee biomechanics when compared to a preplanned task indicating the cutting direction already before the run. The findings of Besier et al. [7] are in line with a later systematic review of experimental trials, showing that unplanned movements lead to changes in lower limb kinetics and kinematics, which are suggestive of an increased injury risk [8].

Recently, Giesche et al. [9] and Niederer et al. [10] found that indicating the required landing leg not before but during a jump to causes a substantial amount of erroneous task executions. Generally, performing an inadequate reactive motor action may trigger injury (e.g. if subsequently colliding with an opponent) or compromise performance (e.g. if subsequently losing the ball). Athletic task safety can hence be decreased not only from a biomechanical but also from a functional point of view.

Although it is highly plausible that the ability to safely perform unplanned cutting/landing tasks under time pressures is dependent on PCF, this question has not been examined systematically, hitherto. The present review summarized the available evidence regarding the association between PCF and markers of biomechanical and functional task safety during unplanned athletic movement.

Materials and Methods

A systematic literature review was performed in July and August 2020. It was conducted adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [11] and followed the recommendations for ethical publishing of systematic reviews proposed by Wager and Wiffen [12]. The study was registered in the PROSPERO database (CRD42018089914).

Search Strategy

Two independent investigators (JW, FG) performed a systematic literature search. In a first step, relevant articles, published without date restriction, were identified by means of the online databases MEDLINE (Pubmed) and ScienceDirect. The search term used was ‘(neurocognition OR cognition) AND (unanticipated OR unplanned OR choice-reaction) AND (cutting OR landing)’. In addition, the reference lists of all papers relevant to the research question were checked [13]. As the omission of unpublished data has been shown to potentially bias the result of reviews [14], additional searches were performed in Google Scholar, screening the first 100 hits obtained with the above term.

Inclusion criteria

Experimental trials examining markers of 1) PCF and 2) biomechanical (e.g. joint moments, ground reaction force or postural sway) or functional (e.g. correct decision-making) safety during unplanned movement tasks were included. Papers had to be written in English language and published in peer-reviewed journals. Published PhD theses (indexed in Google Scholar) meeting the criteria were also included and highlighted accordingly.

Data extraction

Using a standardized assessment sheet, two investigators (JW, FG) independently performed the data extraction. The following information were retrieved: participant characteristics, movement task, PGF and biomechanical outcomes and results (*Tab.2*). If trials reported PGF and biomechanical/functional markers of task safety but did not examine potential relations between them (e.g. by means of correlation analyses or inference statistics), we requested the raw data from the corresponding authors in order to perform the respective calculations.

Study quality and Synthesis of Evidence

Two examiners (JW/FG) independently rated study quality by means of an adapted version of the Downs and Black checklist [15]. It has been proven as feasible and reliable tool to assess the methodological characteristics of randomized and non-randomized studies [15,16]. Our modified instrument included a maximum number of 16 items grouped into four categories: reporting quality, external validity, internal validity (risk of bias), and power (*Tab. 1*). For each criterion met, 1 point was awarded and a sum score (maximum 16 points) was calculated.

The recommendations of the Cochrane Collaboration Back Review Group [17] were applied to rate the available evidence as strong (consistent findings of multiple high-quality studies), moderate (consistent findings among multiple low-quality studies and/or one high-quality study), conflicting (inconsistent findings among multiple studies) or not existent (no studies available).

Results

Search results

The literature search (*Fig. 1*) returned 421 potentially relevant studies. After removal of duplicates and application of exclusion criteria, four cross-sectional studies [9,18–20] and one crossover study [10] were included (*Tab.1*). Raw data had to be requested from the authors of one paper [10]. Methodological quality was high (mean: 13.5/16 points), ranging from 11 to 16 points (*Tab. 2*).

Individual study findings

The experimental set-up of Herman and Barth [18] required an initial jump from a 30-cm box onto a force plate. Shortly (250 ms) before landing, a second target (frontal left, frontal right or same force plate), which had to be reached with an immediate rebound, was indicated on a screen. No pre-planned control condition was completed by the recreationally active participants. The authors divided their sample into a low (LP) and high (HP) cognitive performer group using a computer-based assessment of reaction time, visual scanning and object recognition (Concussion Resolution Index). The LP group produced 31% higher peak vertical ground reaction forces, 26% higher tibial anterior shear forces and 15-fold higher knee abduction moments. Furthermore, LP landed with greater knee abduction (6.1 ± 4.7 vs. 1.3 ± 5.6) and smaller trunk flexion angles (9.6 ± 9.6 vs. 16.4 vs. 11.2°).

Shibata et al. [18] let female university elite athletes perform single-leg (dominant limb) drop jump landings from a 30 cm box onto a force plate, which were followed by one of three maneuvers: a side cut, maintenance of the single-leg stance, or a forward step. Again, only unplanned trials were performed and participants were grouped in HP and LP based on a pen-and-paper test (Symbol Digit Modality test), which captures psychomotor speed, visual short-term memory, attention and concentration. No differences in hip and knee peak joint angles, joint moments and electromyographic Hamstring muscle activity were found. However, the LP group exhibited higher quadriceps activity 50 ms before (+93%) and in the 50 ms after the initial ground contact (+70%). This resulted in a smaller Hamstrings-to-quadriceps co-contraction ratio both, pre- (-63%) and post-initial contact (-45%).

In the study of Almonroeder [20], females (physically active at least on recreational level) jumped onto a force plate to complete either a single-leg landing, a bilateral landing with a vertical jump or a single-leg landing with a lateral cut. Both, pre-planned (required landing maneuver indicated prior to the jump) and unplanned trials (indication during flight) were examined. Only the side cutting on the non-dominant limb during the first 100 milliseconds after initial contact was analyzed. Participants were categorized into LP/FP using the computer-based ImPACT test battery capturing cognitive processing speed. No significant group x condition interactions were found, neither for knee and hip angles and knee moments nor for stance time (latency between landing and cutting). However, there was a significant group main effect, indicating that the LP group demonstrated significantly higher ground reaction forces in both the pre-planned (+17%) and unplanned condition (+20%).

Giesche et al. [9] instructed male recreational athletes to perform counter-movement on a pressure plate. The required landing leg was indicated either prior to the jump (pre-planned) or during the flight phase (unplanned). The authors examined correlations between PGF (multiple computer and pen-and-paper-based tests) and 1) unplanned biomechanical landing costs (difference between planned and unanticipated landings) as well as 2) landing (using the wrong or both legs) / standing (inability to maintain a stable stance after landing) errors. With regard to postural sway (center of pressure path length), unplanned landing costs correlated with lower interference control (Stroop word-color interference test; r = 0.48). Furthermore, significant relationships between an increased number of unplanned landing errors and lower working memory/cognitive flexibility (Trail-Making-Test; TMT-B, r = 0.54; TMT-B vs. A, r = 0.47) as well as short-term memory (Digit Span test, r = 0.55) were found. Finally, the amount of standing errors correlated with better working memory/cognitive flexibility (TMT-B, r = 0.48) and short-term memory (Digit Span test, r = 0.50).

Niederer et al. [10] investigated the acute effects of different warm-up interventions and neuromuscular fatigue on single-leg landing biomechanics, landing success (landing/standing errors) and cognitive function (TMT-A and B capturing visual-perception working memory/cognitive flexibility) using a randomized-controlled crossover design. The experimental set-up was identical to the study of [9] but only unplanned tasks were performed. Our statistical analyses of the original data sent by the authors (control warm-up/pre-fatigue condition) revealed a significant relationship between the amount of landing errors (defined as landing on wrong side or inability to maintain a stable stance after ground contact) and lower visual scanning (TMT-A; r = 0.7). Landing biomechanics (time to stabilization, peak ground reaction force) did not correlate with PGF although a non-significant trend (p<.01) for a possible association between higher peak ground reaction forces and lower cognitive flexibility (TMT-B vs. A difference, r = 0.45) was identified.

Synthesis of the available evidence

The ratings of the available evidence, stratified for the used outcomes, are displayed in *Tab.3*. Evidence was classified as conflicting for both, the associations between PCF and biomechanical task safety as well as PCF and functional task safety during unplanned athletic movement (inconsistent findings of multiple high-quality studies).

Discussion

Although a large body of evidence has revealed that the performance of unplanned sports-related movement patterns is associated with biomechanical aberrations suggestive of increased injury risk [8], there is still a scarcity of studies investigating the underlying mechanism. Our review identified only five studies addressing the potential link between a) PCF and b) changes in biomechanics and functional task safety during cutting or landing tasks requiring time-constrained decision-making. Besides the fact that a larger number of studies is warranted, evidence from the available papers is conflicting and leading to potentially ambiguous conclusions.

On the one hand, with the exception of the thesis from Almonroeder [20], all analysed studies indicated a possible impact of PGF on landing or cutting safety in at least one parameter. Superior PGF may enable athletes to make more rapid and accurate decisions under high time-constraints. Compared to individuals with lower PGF, such accelerated cognitive processing of external stimuli arguably provides additional time to correct inadequate movements and plan upcoming motor actions. Coaches wanting to increase sports performance may hence consider implementing screenings and exercises requiring time-constrained decision-making during sports-related movement. The potential association between PGF

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and unplanned movement safety could also be relevant from an injury-preventive perspective. Faster and more precise decision-making may enlarge the time frame to produce feedforward muscle activity, which is considered crucial to ensure joint stability after ground contact, e.g. following a jump [21]. Interestingly, initial evidence indeed indicates that lower baseline (pre-season) PGF predisposes for non-contact injuries of the lower limb [22–24].

However, on the other hand, when considering the findings of our review in more detail, several aspects call for further research. Firstly, besides participant characteristics (e.g. sex and sports expertise level) the chosen outcomes and the statistical analyses performed were highly heterogeneous between studies, which makes generalizations impossible. Secondly, only two [9,20] out of five studies compared pre-planned and unplanned movement tasks. While correlations between lower PGF and unfavorable biomechanics or inadequate motor actions during unplanned movements are intriguing findings, they could only be interpreted as a proof of causality if a similar association does not exist in pre-planned trials. In other words: future studies examining PGF and unplanned task safety require an adequate control condition (i.e. pre-planned movement task). Finally, the PGF tests used in the included studies mainly targeted lower-order cognitive skills such as processing speed, reaction time or visual scanning. In football (soccer), a typical interactive sport, executive function, which is an example of the more complex higher-order skills (e.g. working memory, cognitive flexibility, inhibitory control; [25,26]), has been identified as a predictor of performance [27–29]. Interestingly, while higher-order skills seem to discriminate elite athletes from amateur and recreational athletes, no difference between both populations can be found for lower-order PGF [29]. As jump landings and cuts represent typical movement patterns in football, we argue that biomechanical and functional task safety under unplanned circumstances requiring time-constrained decision-making will particularly depend on higher order functions.

Conclusions

The findings of the present systematic review provide initial evidence for potential link between PCF biomechanics and functional task safety during cutting or landing tasks requiring time-constrained decision-making. However, although the methodological quality of the included trials was high,

 doi:10.20944/preprints202008.0394.v1

evidence from the available papers is conflicting and leading to potentially ambiguous conclusions. Therefore, future studies are highly warranted considering the implementation of pre-planned control condition and higher-order cognitive testing.

Acknowledgements: -

Author contributions: Conceptualization, J.W.; Methodology, J.W. and F.G.; Analysis/Investigation, J.W. and F.G.; Investigation, Writing – Original Draft Preparation, J.W. and F.G.; Interpretation, J.W., F.G., W.B., D.G.; Writing – Review & Editing, J.W., F.G., W.B., D.G.; Visualization, J.W., F.G., W.B., D.G.

Conflict of Interest: The authors declare no conflict of interest.

 doi:10.20944/preprints202008.0394.v1

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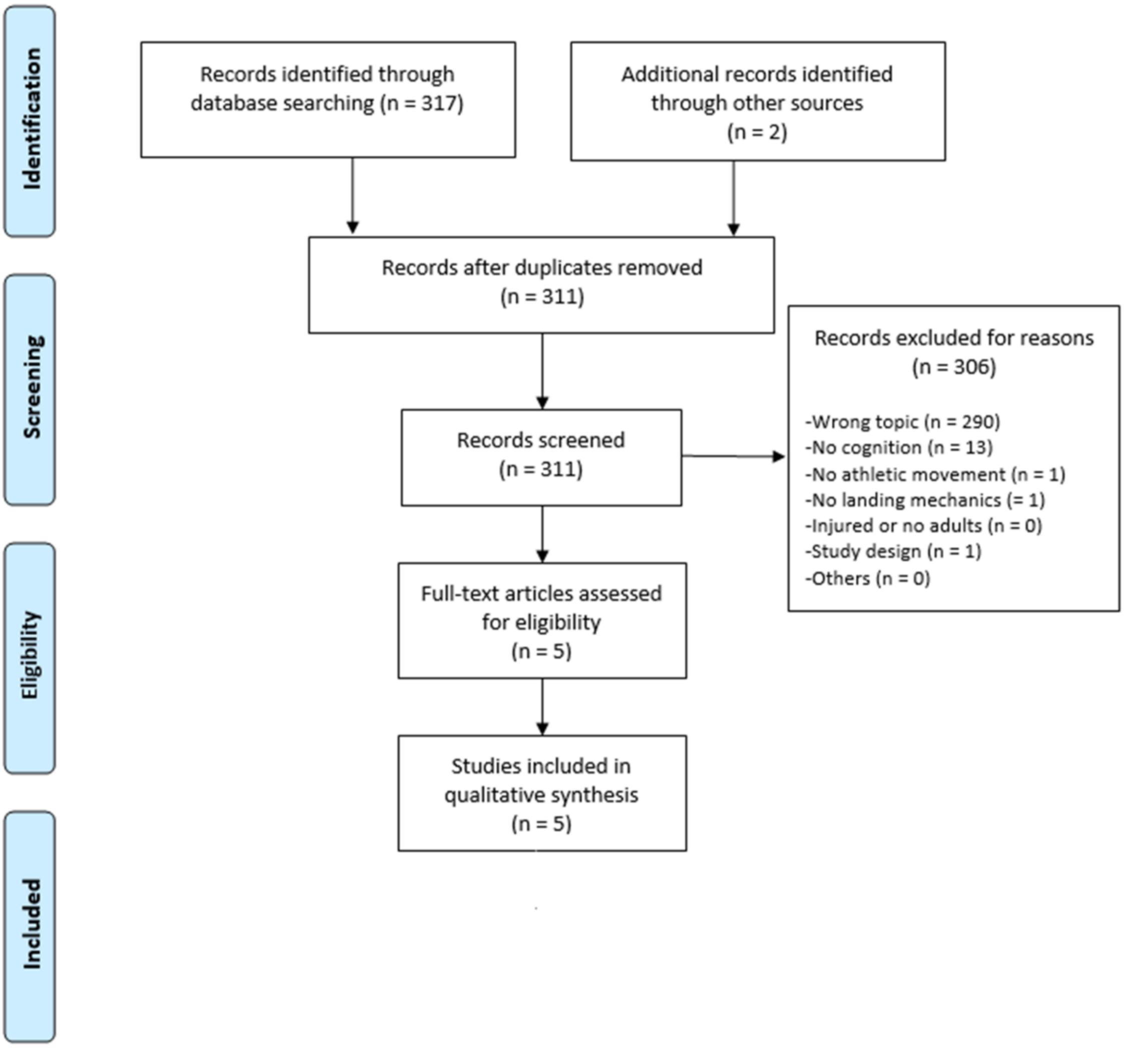
 doi:10.20944/preprints202008.0394.v1

Fig. 1 Chart displaying the literature search



 doi:10.20944/preprints202008.0394.v1

Tab. 2 Study quality (adapted Black and Down Checklist)

	Herman et al. [17]	Shibata et al. [18]	Almonroeder* et al. [19]	Giesche et al. [8]	Niederer et al. [9]
Aim	1	1	1	1	1
Outcomes	1	1	1	1	1
Sample	1	1	1	1	1
Motor task/ conditions	1	1	1	1	1
Confounders	1	1	0	1	1
Findings	1	1	1	1	1
Variability estimates	1	1	1	1	1
Actual p-values	1	1	1	1	0
Funding	1	0	1	1	0
Subscore Reporting	**9/9**	**8/9**	**8/9**	**9/9**	**7/9**
Participants representative	0	0	0	0	0
Setting representative	1	1	1	1	1
Subscore External validity	**1/2**	**1/2**	**1/2**	**1/2**	**1/2**
Data dredging	NA	NA	NA	NA	NA
Adequate statistics	1	1	1	1	1
Subscore Internal validity	**1/1**	**1/1**	**1/1**	**1/1**	**1/1**
Accurate measures	1	1	1	1	1
Randomization of conditions	1	1	1	1	1
Adjustment for confounders	0	1	0	0	0
Subscore Internal validity-confounding	**2/3**	**3/3**	**2/3**	**2/3**	**2/3**
Sufficient power	1	0	1	0	0
Subscore Power	**1/1**	**0/1**	**1/1**	**0/1**	**0/1**
Total Score	**14/16**	**13/16**	**13/16**	**13/16**	**11/16**

*PhD thesis, N/A: not applicable

Tab. 1 Characteristics of the included studies

Study	Participants	Movement task	Outcomes	Statistics
Herman et al. [17]	123 healthy participants (former high school varsity athletes, landing/cutting sports ≥ 1/month) screened; 37 participants enrolled (18 males, 18 females, mean age 21 years); (Cross-sectional design)	*Unanticipated drop-jump landing* Forward jump from 30 cm box on force plate with immediate rebound (bilateral) to a second target (left, right or vertical; visual cue indicating target position displayed 250 ms before landing on first force plate); dominant limb assessed	*Biomechanics:* 3D kinematic and kinetic data of the dominant limb and trunk *Cognitive function:* computerized test (CRI) to capture simple and complex reaction time/processing speed, visual scanning	Participants subdivided into HP (average CRI percentile, 78th) and LP (average CRI percentile, 41st) group based on total score of cognitive testing; Between-group differences (biomechanics)
Shibata et al. [18]	15 healthy female athletes (age: 20.1 ± 1.3 years, BMI: 21.7 Kg/m^2), jumping/cutting sports in university athletic clubs at highest national competition level (2-3 training hours daily, 5-6 days/week); (Cross-sectional design)	*Unanticipated single-leg landing with side-cutting* Drop-jump (30 cm box) on force plate with subsequent maneuvers (dominant limb): -side-step cutting 45°(CUT) -single-leg landing (LAND) -forward stepping (STEP) (arrow indicating the required movement task after leaving the box, displayed on screen; only CUT analyzed)	3D kinematic and kinetic data (dominant limb), averaged muscle activity (%MVC): HAM, QUAD, CCR (ratio: QUAD : HAM (recorded pre-/post-IC) *Cognitive function:* pen-and-paper test (SDMT) to capture psychomotor speed, visual short-term memory, attention and concentration	Participants subdivided into HP vs. LP group on total score of cognitive testing (median); Between-group differences (biomechanics, muscle activity)
Almonroeder* et al. [19]	45 healthy females (age: 18 to 25 years) currently/ previously competing in landing/cutting sports at least at recreational level; (Cross-sectional design)	*Single-leg landing with anticipated and unanticipated side-cutting:* Forward jump (1.5 m) from standing position on force plates with subsequent maneuvers: 1) lateral cut on non-dominant limb, 2) single-leg landing on non-dominant limb, 3) bilateral landing and vertical jump (only cutting analyzed) *Conditions:* 1) anticipated (landing maneuver known before jump)	*Biomechanics:* 3D kinematics and kinetics and stance time (between landing and cutting) of non-dominant limb), *Cognitive function:* ImPACT (computerized) reaction time test (processing speed)	Slow (> 0.59 sec) vs. fast (< 0.52 sec) reaction time group based on Impact reaction time test. 2 x 2 ANOVA (group, condition)

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		2) unanticipated (visual stimulus indicating required maneuver displayed only 350 ms prior landing)		
Giesche et al. [8]	20 healthy males (age: 27.1 ± 4.2 years, BMI: 24.8 ± 3.03 kg/m^2), physically active (at least at recreational level); (Cross-sectional design)	*Jump with anticipated and unanticipated single-leg landing* Counter-movement jump on capacitive pressure plate (both limbs assessed) with (1) left foot landing or (2) right foot landing *Conditions:* 1) anticipated (required landing side known before jump) 2) unanticipated (visual stimulus indicating required landing side displayed only during jump ~360 ms prior landing)	*Biomechanics:* pVGRF, landing postures (COP path length, TTS, standing errors) Decision-making quality: landing errors (landing on wrong or both sides) in unplanned trials *Cognitive function:* computerized and pen-and-paper tests (TMT-A, B), Stroop I, II, III, digit spans test, Stop-signal task, reaction time/processing speed via CogState test battery to capture higher level (cognitive flexibility, working memory, inhibitory and interference control) and lower-level (visual-perception, simple reaction time, short-term memory) cognitive functions	Between condition differences (biomechanics, decision-making quality) to detect unplanned landing costs (significantly decremental landing stability relative to planned trials); Association beween individual cognitive functions and unanticipated landing costs
Niederer et al. [9]	19 recruited and 18 healthy, physically active participants (8 males; age: 25 ± 2 years, Weight: 68 ± 10 kg) included. (Crossover design)	*Unanticipated single-leg landing* Counter-movement jump on capacitive pressure plate (both limbs assessed) with (1) left foot landing or (2) right foot landing (visual stimulus indicating required landing side displayed only during jump)	*Biomechanics/landing success:* pVGRF, landing postures (TTS, landing and standing errors) *Cognitive function:* pen-and-paper tests (TMT-A, B); outcomes assessed after either a functional, classic or control warm-up (movie) protocol pre- and post-neuromuscular fatigue protocol.	3 (warm-up) x 2 (pre-to post-fatigue ANCOVA (covariates; baseline values and fatigue jump times) or pre-to post-changes via Friedman testing **

CRI = Concussion Resolution Index, LP = low performance group, HP = High performance group, SDMT = The Symbol Digit Modalities Test, MVS = maximum voluntary contraction, HAM = Hamstrings, QUAD = Quadriceps, CCR = co-contraction ratio, pre-IC = before initial contact, post-IC = first 50 ms after initial contact, pVGRF = peak vertical ground reaction force, COP = Center of pressure path length, TTS = Time to stabilisation, TMT = Trail-Making-Test, Stroop I = read words, Stroop II = name colors, Stroop III = word-color interference test; * PhD thesis. ** The original data was provided by Niederer et al. on request. Based on this, we conducted the statistical analyses regarding potential relationships between unanticipated landing biomechanics/success and cognitive function ourselves using the control warm-up condition (movie) at pre-fatigue only.

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Tab. 3. Synthesized Results of the relation between perceptual-cognitive function and unplanned task safety

	Biomechanical task safety	**Functional task safety**
Herman et al. [17]	↓	
Shibata et al. [18]	↓	
Almonroeder et al. [19]	-	
Giesche et al. [8]	↓	?
Niederer et al. [9]	?	↓
Rating of evidence	conflicting	conflicting

Dark grey shaded fields: parameter not examined, ↓= decrease in parameter, - = no difference in parameter, ? = conflicting results