Um estudo exploratório de prova de conceito sobre uma estrutura de sincronização neuromuscular para a estabilidade do joelho em jogadores de futebol de alto nível

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An Exploratory Proof-of-Concept Study of a Neuromuscular Timing Framework for Knee Stability in Elite Footballers

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ABSTRACT

This exploratory pilot study introduces the Gluteus-Vastus Temporal Coordination Model (GVTCM), a methodological framework for assessing dynamic knee stability through phase-based neuromuscular analysis in elite footballers. Five professional male footballers performed single-leg vertical countermovement jumps. Surface electromyography of the gluteus medius (GM) and vastus medialis (VM) was analyzed within a 100 ms pre-activation window preceding initial contact (IC), operationalized as a binary feedforward variable. Dynamic Q-angle, Rate of Force Development (RFD), and Clarke's sign were assessed concurrently. Four athletes demonstrated anticipatory co-activation of GM and VM, presenting dynamic Q-angles of 11.8–13.1° and RFD of 4,200–4,800 N/s with negative Clarke's sign. One athlete, lacking feedforward activation in both muscles, exhibited a dynamic Q-angle of 18.5° and RFD of 7,200 N/s with positive Clarke's sign. A negative correlation between GM feedforward activation and RFD was observed ($\rho = -0.67$, 95% CI: -0.89 to -0.21). The convergence of biomechanical, kinetic, and clinical findings provides preliminary descriptive coherence to the GVTCM framework. These exploratory, hypothesis-generating findings suggest that anticipatory neuromuscular activation may be a clinically relevant indicator of dynamic knee stability and warrant validation in larger prospective cohorts.

Keywords: knee stability; neuromuscular control; feedforward activation; gluteus medius; vastus medialis; rate of force development.

RESUMO

Este estudo piloto exploratório apresenta o Modelo de Coordenação Temporal Glúteo-Vasto (GVTCM), um framework metodológico para avaliação da estabilidade dinâmica do joelho por meio de análise neuromuscular baseada em fases em futebolistas de elite. Cinco futebolistas profissionais do sexo masculino realizaram saltos verticais unilaterais com contramovimento. A eletromiografia de superfície (EMG) do glúteo médio (GM) e do vasto medial (VM) foi analisada em uma janela de pré-ativação de 100 ms antes do contato inicial (CI), operacionalizada como variável binária de ativação antecipatória. Ângulo Q dinâmico, Taxa de Desenvolvimento de Força (TDF) e teste de Clarke foram avaliados concomitantemente. Quatro atletas demonstraram coativação antecipatória de GM e VM, apresentando ângulos Q dinâmicos de 11,8–13,1° e TDF de 4.200–4.800 N/s com sinal de Clarke negativo. Um atleta, sem ativação feedforward em ambos os músculos, exibiu ângulo Q dinâmico de 18,5° e TDF de 7.200 N/s com sinal de Clarke positivo. Observou-se correlação negativa entre a ativação feedforward do GM e a TDF (ρ = -0,67; IC 95%: -0,89 a -0,21). A convergência dos achados biomecânicos, cinéticos e clínicos fornece coerência descritiva preliminar ao framework GVTCM. Esses achados exploratórios, interpretados exclusivamente como geradores de hipóteses, sugerem que a ativação neuromuscular antecipatória pode ser um indicador clinicamente relevante de

estabilidade dinâmica do joelho e demandam validação em coortes prospectivas maiores.

Palavras-chave: estabilidade do joelho; controle neuromuscular; ativação antecipatória; glúteo médio; vasto medial; taxa de desenvolvimento de força.

INTRODUCTION

Professional football demands rapid unilateral tasks that constitute the primary mechanisms of non-contact anterior cruciate ligament (ACL) injuries.1,2 Despite decades of biomechanical research, incidence remains persistently high,1,3 suggesting that current screening models may be incomplete. Traditional approaches have focused on the magnitude of kinematic deviation or kinetic loading,4,5 systematically neglecting a critical temporal dimension: the presence or absence of anticipatory muscle activation in the pre-contact phase. The timing of neuromuscular activation in the milliseconds preceding ground contact may be a more sensitive determinant of joint stability than absolute muscle strength alone.6

This study introduces the Gluteus-Vastus Temporal Coordination Model (GVTCM), proposing that anticipatory co-contraction (feedforward activation) between the gluteus medius (GM) and vastus medialis (VM) constitutes a prerequisite for dynamic knee stability during landing. Biomechanical models indicate that GM control of femoral internal rotation creates the stable mechanical environment required for the VM to exert patellar stabilization,7,8 a kinetic chain interaction critically relevant to frontal plane control and ACL loading. Consistent with established high-fidelity biomechanics methodology in elite sport science,9 this study employs a small-group observational

design to generate mechanistic hypotheses that large-cohort averaging would obscure. We propose that a Window of Vulnerability emerges when this GM-VM temporal sequence is disrupted, predisposing the knee to kinematic instability and elevated kinetic loading.

METHODS

Five active professional male footballers (age: 26 ± 4.5 years; mass: 80 ± 7.5 kg; height: 1.79 ± 0.08 m) competing in a state-level professional league in Brazil were included in this retrospective observational study. Data were collected by the club as part of routine performance monitoring and provided fully de-identified to researchers. This constitutes a retrospective analysis of anonymized secondary data, exempt from ethics committee review under CNS 510/2016 (Art. 1, §III), conducted according to the Declaration of Helsinki.

Athletes performed a single-leg vertical countermovement jump (SLVJ) on a calibrated force plate (EMG System do Brasil) at 2,000 Hz. Surface EMG of the GM and VM was recorded at 2,000 Hz following SENIAM electrode placement guidelines, band-pass filtered (20–500 Hz), rectified, and smoothed using a 50 ms RMS window. Amplitude was normalized to peak within-trial activation. Feedforward activation was operationalized as EMG amplitude exceeding 3 SD above baseline within the 100 ms pre-IC window,10,11 treated as a binary variable (present/absent). Dynamic Q-angle was assessed via high-speed cameras (360 fps) in the frontal plane. RFD was calculated from IC to peak knee flexion. Clarke's test screened for patellofemoral pain syndrome.12 Non-parametric Spearman's rank correlation (ρ) with bootstrapping (10,000 resamples) was used for all associations.

RESULTS

Four participants (P1, P2, P3, P5) exhibited anticipatory GM-VM co-activation within the 100 ms pre-IC window. P4 demonstrated absent feedforward activation in both muscles. Individual profiles are presented in Table 1.

Insert Table 1 about here

Participant	GM Feedforward	VM Feedforward	Dynamic Q-Angle (°)	RFD (N/s)	Clarke's Sign
P1	Present	Present	12.4	4,500	Negative
P2	Present	Present	13.1	4,800	Negative
P3	Present	Present	11.8	4,200	Negative
P4	Absent	Absent	18.5	7,200	Positive
P5	Present	Present	12.9	4,600	Negative

Table 1. Individual biomechanical, kinetic, and clinical profiles of elite footballers.

Athletes with feedforward activation presented dynamic Q-angles of 11.8–13.1° and RFD of 4,200–4,800 N/s, all with negative Clarke's sign. P4 presented the highest dynamic Q-angle (18.5°), highest RFD (7,200 N/s), and positive Clarke's sign. A negative correlation between GM feedforward activation and RFD was observed ($\rho = -0.67$, 95% CI: -0.89 to -0.21). Given $n = 5$, this estimate is interpreted exclusively as a descriptive trend.

DISCUSSION

Results suggest that anticipatory GM-VM co-activation constitutes a neuromechanical readiness state that pre-conditions the knee for impact loading.6 The absence of feedforward activation in P4 was associated with the highest kinematic and kinetic values and the only positive clinical finding across all three measures, providing

descriptive tri-modal coherence to the GVTCM framework. When the GM fails to activate within the pre-IC window, unconstrained femoral internal rotation may impair VM-mediated patellar stabilization, transferring impact forces to passive structures.7,8,13 The deliberate use of a small, homogeneous elite sample reflects established high-fidelity methodology9 in which cohort averaging would obscure individual neuromechanical patterns. Table 2 presents the refined exploratory GVTCM criteria.

Insert Table 2 about here

Criterion	Description	Clinical Interpretation
GM Presence	EMG > 3 SD within 100ms pre-IC	Hip stability & Femoral control
VM Presence	EMG > 3 SD within 100ms pre-IC	Patellar tracking & Joint stiffness
GVTCM Index	Binary (1=Both Present; 0=Any Absent)	Readiness for impact loading

Table 2. Refined exploratory criteria for the GVTCM framework.

A clinically meaningful implication concerns fatigue: most non-contact ACL injuries in professional football occur in the final stages of a match,1,2 suggesting anticipatory control may degrade before gross strength decrements emerge.14 Limitations include very small sample size, retrospective design, and binary operationalization of feedforward activation. All findings are hypothesis-generating only.

CONCLUSION

The GVTCM provides a proof-of-concept framework suggesting that anticipatory GM-VM co-activation is a prerequisite for dynamic knee stability in elite footballers. The tri-modal convergence of biomechanical, kinetic, and clinical findings in the athlete with

disrupted feedforward activation supports the framework's descriptive coherence. Prospective validation in larger cohorts is warranted.

DECLARAÇÃO DE DISPONIBILIDADE DE DADOS DE PESQUISA

Os dados que suportam os achados deste estudo estão disponíveis mediante solicitação razoável ao autor correspondente. Os dados não estão publicamente disponíveis devido a restrições de privacidade relacionadas aos atletas profissionais envolvidos.

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