

UNIVERSIDADE FEDERAL DE MINAS GERAIS
Escola de Educação Física, Fisioterapia e Terapia Ocupacional
Programa de Pós-graduação em Ciências da Reabilitação

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**INFLUÊNCIA DA INTENSIDADE DA CORRIDA E DO TEMPO DE
RECUPERAÇÃO NA CINEMÁTICA, COORDENAÇÃO E REGULARIDADE DOS
MEMBROS INFERIORES DURANTE A TAREFA DE AGACHAMENTO
UNIPODAL EM PRATICANTES DE CORRIDA**

Belo Horizonte

2023

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UNIPODAL EM PRATICANTES DE CORRIDA**

Tese apresentada ao Programa de Pós-graduação em Ciências da Reabilitação da Escola de Educação Física, Fisioterapia e Terapia Ocupacional da Universidade Federal de Minas Gerais como requisito parcial à obtenção do título de Doutora em Ciências da Reabilitação.

Linha de Pesquisa: Estudo do Desempenho Motor e Funcional Humano

Orientador: Prof. Dr. Sérgio Teixeira Fonseca

Coorientadora: Prof. Dra. Juliana Melo Ocarino

Coorientador: Prof. Dr. Richard Van Emmerik

Belo Horizonte

2023

A657i Aquino, Mariana Rodrigues Carvalho de
2023 Influência da intensidade da corrida e do tempo de recuperação na cinemática, coordenação e regularidade dos membros inferiores durante a tarefa de agachamento unipodal em praticantes de corrida. [manuscrito] / Mariana Rodrigues Carvalho de Aquino – 2023.
111 f.: il.

Orientador: Sérgio Teixeira da Fonseca
Coorientador: Richard Van Emmerik
Coorientadora: Juliana de Melo Ocarino

Tese (Doutorado) – Universidade Federal de Minas Gerais, Escola de Educação Física, Fisioterapia e Terapia Ocupacional.

Bibliografia: f. 97-102

1. Corredores - Teses. 2. Cinemática - Teses. 3. Membros inferiores - Teses. I. Fonseca, Sérgio Teixeira da Fonseca. II. Emmerik, Richard Van. III. Ocarino, Juliana de Melo. IV. Universidade Federal de Minas Gerais. Escola de Educação Física, Fisioterapia e Terapia Ocupacional. V. Título.

CDU: 612:76



UNIVERSIDADE FEDERAL DE MINAS GERAIS

PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DA REABILITAÇÃO



ATA DA DEFESA DE TESE DA ALUNA MARIANA RODRIGUES CARVALHO DE AQUINO

Realizou-se, no dia 14 de novembro de 2023, às 14:00 horas, Auditório Maria Lúcia Paixão, da Universidade Federal de Minas Gerais, a defesa de tese, intitulada *Influência da intensidade da corrida e do tempo de recuperação sobre a cinemática, coordenação e regularidade dos membros inferiores durante a tarefa de agachamento unipodal em praticantes de corrida.*, apresentada por MARIANA RODRIGUES CARVALHO DE AQUINO, número de registro 2019713793, graduada no curso de FISIOTERAPIA, como requisito parcial para a obtenção do grau de Doutor em CIÊNCIAS DA REABILITAÇÃO, à seguinte Comissão Examinadora: Prof(a). Sérgio Teixeira da Fonseca - Orientador (UFMG), Prof(a). Juliana de Melo Ocarino (UFMG), Prof(a). Fábio Viadanna Serrão (Universidade Federal de São Carlos), Prof(a). Carlos Marcelo Pastre (UNESP - Presidente Prudente), Prof(a). Thales Rezende de Souza (UFMG), Prof(a). Michael Busa (University of Massachusetts Amherst), Prof(a). Richard E.A. Van Emmerik (University of Massachusetts Amherst).

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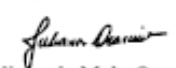
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Belo Horizonte, 14 de novembro de 2023.


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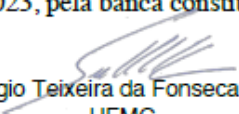
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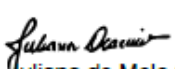
Influência da intensidade da corrida e do tempo de recuperação sobre a cinemática, coordenação e regularidade dos membros inferiores durante a tarefa de agachamento unipodal em praticantes de corrida.

MARIANA RODRIGUES CARVALHO DE AQUINO

Tese submetida à Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em CIÊNCIAS DA REABILITAÇÃO, como requisito para obtenção do grau de Doutor em CIÊNCIAS DA REABILITAÇÃO, área de concentração DESEMPENHO FUNCIONAL HUMANO.

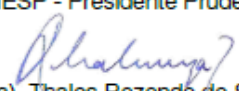
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Belo Horizonte, 14 de novembro de 2023.

AGRADECIMENTOS

Nem parece que já se passaram quatro anos! Apesar do esforço e tempo dedicado ao longo dessa trajetória, foi um processo tão leve e prazeroso, que fico na dúvida se queria que terminasse. Mas isso só foi possível porque tive pessoas maravilhosas e essências que estiveram ao meu lado. Por isso, agradeço primeiramente a Deus por me dar força e iluminar o meu caminho com pessoas que mais parecem anjos de tão especiais.

Agradeço a minha família, base de tudo! À minha mãe, Eliane, obrigada por tudo. Obrigada por me ensinar a correr atrás dos meus sonhos, me apoiar e sempre me incentivar a crescer e ser uma pessoa melhor. Aos meus três irmãos (Matheus, Bruno e Victor) por sempre estar do meu lado, me socorrendo e comemorando comigo em todos os momentos da minha vida. Ao meu sobrinho mais lindo (Arthur) por tornar a vida da Tia Mari muito mais feliz e alegre. Obrigada pai (José Mario) pelo carinho e amor de sempre. Agradeço também meu padasto (Rommel) pelo apoio e risada por todos esses anos. Às minhas cunhadas maravilhosas (Renata e Cris) e suas famílias por sempre estarem por perto. Minha 'veinha' (Suzana) que mesmo morando na Lua - como diz o Arthur - sempre acompanhou e torceu pelo sucesso da sua netinha. A todos os meus familiares que sempre se fazem presentes, contribuindo e torcendo por mim. Muito obrigada família, amo muito vocês!

Preciso fazer o próximo agradecimento em inglês.

I can't talk about family and not mention my American Family. George, Beth, Jill, Steve, Meg, Aida, Keillan, Lucas and the entire Drew's family, I can't thank you enough for being part of my life. Mom, dad, and sis, after everything you have done for me, I truly believe you are my guardian angels. You have encouraged me, supported me, and celebrated with me every step I take in my life. I love you all so much!

Agradeço aqueles que são a família que escolhemos ao longo da vida. Agradeço ao Vinícius pelo amor, parceria, e aprendizado ao longo desses anos. Seu apoio foi fundamental nos momentos de estresse e nos de alegria. Obrigada Bruninha, Bap e Bella, por mais de 20 anos de amizade e cumplicidade. Agradeço a Jeh, Valzinha, Nena, Lala, Carol, Volpini e Jojo por tantos anos de incentivo e divertimento. Obrigada Bruna, Xiol, Fernanda e Dmitri por estarem do meu lado e torcendo por mim, principalmente neste último ano. Obrigada família Barreirense por todos os momentos compartilhados. A todos os meus amigos queridos que fazem parte da minha vida e sempre estiveram por perto me amparando e celebrando comigo.

Agradeço ao meu orientador, Dr. Sérgio Fonseca. Sérgio, que privilégio poder conviver e aprender com você ao longo desses anos! Você transformou esse doutorado em

um processo tão leve e divertido! Me lembro de nossas reuniões que sempre duravam horas e, no final, estávamos nós dois muito animados com o projeto, descobertas, e todas as possibilidades que isso poderia desencadear. Obrigada pela paciência e por sempre estar disponível, mesmo durante todas as minhas visitas não agendadas ou anunciadas no CTE. Com certeza sou uma pessoa, profissional e pesquisadora melhor por ter convivido com você! Obrigada por todas as oportunidades que você me proporcionou e por todos esses anos de parceria. Tenho certeza de que iremos continuar essa parceria por mais tempo, pois ainda temos todos aqueles planos e ideias para realizar. Após ser sua aluna sou, não só uma atleta de classe internacional, mas uma aluna premiada internacional (haha)!

Agradeço à minha coorientadora, Dra. Juliana Ocarino. Ju, obrigada por me acolher e me acompanhar nesta caminhada desde o mestrado. Obrigada pelos ensinamentos e oportunidades ao longo desses anos. Agradeço também ao Dr. Renan Resende e Dr. Thales Souza, por me acompanharem de perto desde a graduação, sempre disponíveis e contribuindo para o meu crescimento. Vocês três são exemplos de profissionais que tive a sorte de ter presente na minha vida. Aos professores do Programa de Pós-graduação em Ciências da Reabilitação, muito obrigada pelos conhecimentos e crescimento que me proporcionaram! Agradeço também aos membros da banca, Dr. Fábio Serrão e Dr. Carlos Marcelo Pastre. Obrigada pela disponibilidade e empenho de vocês em contribuírem com esse processo e com a minha formação.

Agradeço também a toda a equipe do Laboratório de Análise de Movimento (LAM). Como é bom poder trabalhar ao lado de pessoas tão competentes. Em especial, obrigada Dra. Priscila Araújo, Dra. Líria Nobrega e Délcio. Prips, que privilégio poder aprender a queimar muitos neurônios com você. Você foi fundamental nesse doutorado! Líria, obrigada pelo apoio, carinho e cuidado comigo nesses anos. Esse laboratório estaria completamente perdido sem você. Délcio, muito obrigada por sempre estar por perto e pronto para ajudar diante de qualquer dificuldade. Obrigada a todos os mestrandos, doutorandos, alunos e professores por compartilharem o laboratório, projetos e conhecimentos comigo. Agradecimento especial para ao Dr. Thiago Teles, Ju Quirino, Renatha Carvalho, Letícia, Bruno, Sabrina e Camila. Que time!

Não posso deixar de agradecer às minhas crianças, Ana Carolina, Fabiane, Jefferson, Rebeca, Pedro, Samá e Vitor. Esse projeto não teria acontecido sem vocês! Obrigada por abraçarem esse projeto como se fosse de vocês, pela paciência comigo e por tantos momentos de aprendizado. Vocês são maravilhosos demais! Agradeço à Eliane, do colegiado, pela

competência e por todo o suporte imediato que sempre me proporcionou. A todos os voluntários que participaram e se comprometeram com o projeto, muito obrigada!!!

Para finalizar, peço licença novamente para fazer o próximo agradecimento em inglês.

A special thanks to my advisor, Dr. Richard Van Emmerik. Richard, thank you for opening your home, hosting me, and making me part of your lab and team for this past year. I learned and grew so much with you during my time in Amherst. Thank you for encouraging me, trusting me and for giving me opportunities to grow.

Another special thanks to Dr. Mike Busa. Mike, thank you for all the knowledge and opportunities you provided me this year. Thank you for trusting me and my work and for giving me the opportunity to work with such a competent person as you.

To my friends for life, Dane, Gal, Josh, Sam, and Athulya. Dane, thank you for being by my side almost 24/7 this past year, for sharing projects and papers, for teaching and for being patient with me. But most of all, thank you for all the talks, laughs, and for always being there when I needed. Gal, thank you for being this sweet and wonderful person that you are, that was always there to support me and make my day better. Josh, thank you for teaching me so much, for rolling your eyes after all my questions but always answering them (haha), for being patient, and for helping me become a better researcher (even against my will sometimes). But mainly, thank you for being my buddy! Sam, thank you for the knowledge, talks, walks, and laughs. Athulya, thank you for being my date and partner during all social events, for teaching me so much, and for sharing important moments in life.

I would like to thank the Department of Kinesiology professors and professionals, Kath, Wouter, Mark, Jane, and Meredith. Finally, thanks to my all students and lab mates in Amherst that helped to make this past year so wonderful. To my UMASS family, thank you so much!

Agradeço a vocês, e todos os outros que de alguma forma contribuíram nesses dois anos de mestrado, com palavras, ações ou pensamentos positivos. Muito obrigada!!!

É com imenso prazer que compartilho essa vitória com todos vocês!

RESUMO

Introdução: Corredores apresentam altas taxas de lesões musculoesqueléticas que estão relacionadas a incapacidade de resistir e recuperar da demanda imposta por rotinas de exercícios e treinamentos. Diferentes intensidades de exercício podem induzir diferentes níveis de fadiga e levar a mudanças na cinemática, padrão coordenativo e regularidade, demandando tempo de recuperação. Desequilíbrios entre o tempo de recuperação e a demanda imposta pelo exercício podem contribuir para o desenvolvimento de lesões. O objetivo geral deste estudo foi investigar a influência da intensidade da corrida e do tempo de recuperação na cinemática, padrão coordenativo, e regularidade dos membros inferiores durante a tarefa de agachamento unipodal e a relação com a ocorrência de lesões em corredores. **Métodos:** Trinta corredores saudáveis realizaram agachamentos unipodal durante 60 segundos pré, pós, 24h e 48h após correr em intensidade moderada (60min, 65%VO₂máx) e intensa (4x15min, 85%VO₂máx), ou descansar (controle). Após seis meses das avaliações, os corredores que sofreram lesão neste período foram comparados com aqueles sem lesão. Cinemática articular (ângulos do tornozelo, joelho, quadril) e padrão coordenativo (fase relativa entre tornozelo-jelho, joelho-quadril) foram investigados pelas análises das curvas médias normalizadas pelo ciclo e da regularidade (*Multiscale Entropy*). Análises de Variância (ANOVA) foram realizadas para verificar os efeitos principais e as interações entre intensidades e protocolos, e entre intensidades, protocolos e grupos. **Resultados:** Aumentos na regularidade (menor entropia) de tornozelo-jelho foram observados após ambos os protocolos de corrida. Corredores que sofreram lesões em até seis meses apresentaram padrão de movimento mais regular e necessitaram de mais tempo para recuperação, comparado com corredores sem lesão. Nenhuma diferença foi observada no pré-teste, após protocolo controle, ou nas análises de curvas médias normalizadas das articulações e coordenações. **Conclusão:** Monitorar mudanças durante uma tarefa funcional pode fornecer informações precoces sobre a capacidade de indivíduos em adaptar e recuperar de treinamentos e exercícios.

Palavras-chave: Agachamento. Lesão musculoesquelética. Corredor. Fase relativa. Entropia.

ABSTRACT

Background: Runners present high rates of musculoskeletal injuries that are related to the inability to resist and recover from the demand imposed by exercise and training routines. Different exercise intensities can induce different levels of fatigue and lead to changes in kinematics, coordination pattern, and regularity, which require time to recover. An imbalance between recovery time and the demands imposed by exercise can contribute to the development of injuries. The main objective of this study was to investigate the influence of running intensity and recovery time on lower limb kinematics, coordination pattern, and regularity during a single-leg squat task and the relationship with the injury occurrence in runners. **Methods:** Thirty healthy recreational runners performed a 60-second single-leg squat task on pre, post, 24 and 48 hours after running at moderate (60min, 65%VO₂max) and high-intensity (4x15min, 85% VO₂max) or rest (control). After six months of assessments, runners who were injured within this period were compared with non-injured runners. Joint kinematics (ankle, knee, and hip angles) and coordination pattern (relative phase between ankle-knee and knee-hip angles) were analyzed using mean cycle-normalized curves and regularity (Multiscale Entropy). ANOVA analyses were performed to verify interactions between protocols (moderate, high, control) and times (pre, post, post24, post48), and between protocols, times, and groups. **Results:** Increases in ankle-knee regularity (lower entropy) were observed after both running protocols. Additionally, the injured group presented a more regular movement pattern and required more time to recover than non-injured group. No differences were observed in the pre-test, after the control protocol, or when evaluating cycle-normalized mean curves of joints and coordination angles. **Conclusion:** Monitoring changes during a functional task can provide important early information about the individuals' ability to adapt and recover from training and exercise.

Keywords: Single-leg squat. Musculoskeletal injury. Runner. Relative phase. Entropy.

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LISTA DE ABREVIATURAS E SIGLAS

FC	Frequência Cardíaca
PSE	Percepção Subjetiva de Esforço
RER	Razão de Troca Respiratória
UFMG	Universidade Federal de Minas Gerais
VCO ₂	Dióxido de Carbono
VO ₂	Volume de Oxigênio
VO ₂ máx	Volume Máximo de Oxigênio

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PREFÁCIO

A presente tese foi elaborada em formato opcional e estruturada de acordo com as normas estabelecidas do Programa de Pós-Graduação em Ciências da Reabilitação da Universidade Federal de Minas Gerais (UFMG). A primeira seção contém a introdução com a problematização, a justificativa do estudo realizado e os objetivos dos dois estudos que compõe a tese. A segunda seção apresenta a parte metodológica comum aos dois estudos e descrita de forma mais detalhada. Em seguida são apresentados os dois estudos escritos em forma de artigo e formatados de acordo com a norma dos periódicos onde serão submetidos: Estudo 1 – a ser submetido no periódico *Journal of Biomechanics*; Estudo 2 – a ser submetido no *British Journal of Sports Medicine*. Em seguida, estão expostas as considerações finais relacionadas aos resultados da tese. Por último, estão indicadas as referências bibliográficas, anexos, e mini currículo.

1 INTRODUÇÃO

A corrida é uma atividade esportiva com alta taxa de lesões musculoesqueléticas (Buist *et al.*, 2010; Gent; Van *et al.*, 2007; Gruber, 2023; Messier *et al.*, 2018; Videbæk *et al.*, 2015). Lesões musculoesqueléticas são processos multifatoriais relacionados a inabilidade de resistir e recuperar das demandas imposta por rotinas de exercícios e treinamentos (Hreljac, 2005; Kellmann *et al.*, 2018; Soligard *et al.*, 2016). Por exemplo, lesões em corredores são, em sua maior parte, por *overuse* e estão associadas com o volume de treino, fadiga neuromuscular e recuperação inapropriada (Hreljac, 2004; Soligard *et al.*, 2016). Além disso, mudanças na cinemática, padrão coordenativo e regularidade podem ser observadas após atividades físicas, mesmo na ausência de esforço máximo ou exaustão (Dierks, Davis e Hamill, 2010; Mo; Chow, 2019; Quirino *et al.*, 2021; Riazati *et al.*, 2020; Santos *et al.*, 2023). Isto é, diferentes intensidades de exercício podem induzir diferentes níveis de fadiga e impactar o padrão de movimento, demandando tempo de recuperação (Dierks, Davis; Hamill, 2010; Kellmann *et al.*, 2018; Monjo, Terrier; Forestier, 2015). Entretanto, maior parte dos estudos avaliaram somente o efeito imediato desconsiderando efeitos prolongados do exercício (Hollman *et al.*, 2020; Möhler, Fadillioglu e Stein, 2021; Smith *et al.*, 2021; Stock *et al.*, 2016). Considerando que sobrecargas de treinamento (i.e., *overtraining*) são comumente observadas em corredores (Meeusen *et al.*, 2013), uma melhor investigação da influência do exercício no padrão de movimento e no tempo de recuperação é necessário (Bishop, Jones; Woods, 2008).

Padrões de movimento funcionais são resultados de interações coordenadas entre os vários componentes neurais, musculares, e metabólicos organizados temporalmente em diferentes escalas temporais (Kelso e Schöner, 1988; Turvey, 1990). A coordenação de movimentos pode ser definida como o domínio dos muitos graus de liberdade disponíveis envolvidos em um determinado movimento (Bernstein, 1967). Dessa forma, a formação de estruturas coordenativas reduz o número de variáveis independentes a serem controladas e permite que o indivíduo produza diferentes soluções para a mesma tarefa (Bernstein, 1967; Kelso e Schöner, 1988; Turvey, 1990). Indivíduos com comportamento mais flexível e adaptativo conseguem otimizar a performance da tarefa (Latash, 2012), enquanto indivíduos com menor capacidade de adaptação (e.g., lesão, patologias, ou idosos) tendem a adotar padrões coordenativos mais regulares e previsíveis em resposta a perturbações (Kiefer *et al.*, 2013; Paterno *et al.*, 2015; Santos *et al.*, 2023). Por exemplo, alterações nos padrões coordenativos têm sido associados a um risco aumentado de lesões, como a ruptura do ligamento cruzado anterior do joelho (Hashemi *et al.*, 2011; Paterno *et al.*, 2015; Stock *et al.*,

2016). Interações entre segmentos ou articulações, ou seja, como o movimento de um segmento influencia no movimento de outro segmento (i.e., padrão coordenativo) vem sendo foco de diferentes estudos e comumente quantificado por meio da análise de fase relativa entre dois segmentos/articulações (e.g., fase relativa contínua) (Hamill *et al.*, 1999; Lamb e Stöckl, 2014). Portanto, avaliar como as articulações interagem e são coordenadas para executar uma tarefa pode fornecer informações mais abrangentes sobre o padrão de movimento adotado em resposta ao exercício, fadiga e recuperação, comparado com análises da cinemática articular isoladamente (Hamill, Palmer e Emmerik, Van, 2012).

Diversos estudos investigaram a influência da fadiga e da recuperação sobre aspectos fisiológicos do sistema musculoesquelético (e.g., aumento da concentração de creatina quinase e lactato, déficit da ativação e força muscular) e observaram consequências que persistiram por até 48 horas após diferentes atividades (Martínez-Navarro *et al.*, 2021; Thomas *et al.*, 2018; Willwacher, Sanno e Brüggemann, 2020; Winter, Gordon e Watt, 2017). Atividades que induzem fadiga neuromuscular podem diminuir a ativação e a força muscular e aumentar o dano muscular, reduzindo a capacidade do sistema musculoesquelético de resistir a perturbações internas e externas (Baumert *et al.*, 2021). Consequências da fadiga sobre o padrão de movimento podem ser experienciadas no cotidiano, após rotinas diárias de treinamento (Monjo, Terrier e Forestier, 2015), e induzir mudanças nos padrões de movimento articulares e coordenativos (Carvalho *et al.*, 2023; Hollman *et al.*, 2020; Schütte *et al.*, 2015). Entretanto, os poucos estudos que investigaram a influência de protocolos de fadiga no padrão de movimento (i.e., cinemática, coordenação) somente avaliaram curtos períodos de recuperação, entre 20 min a 6 horas pós-exercício (Carvalho *et al.*, 2023; Tian *et al.*, 2020; Tsai *et al.*, 2009). Considerando que corredores costumam treinar todos os dias ou em dias alternados, monitoramentos mais longos (e.g., 24 e 48 horas pós-exercício) são necessários para entender o processo de recuperação entre sessões de treinamentos (Hespanhol Junior *et al.*, 2012; Ristolainen *et al.*, 2014). Além disso, a capacidade dos corredores de resistir às demandas do exercício e da fadiga é essencial para diminuir a ocorrência de lesões (Fonseca *et al.*, 2020; Hreljac, 2005). Portanto, mudanças imediatas ou prolongadas nos padrões de movimento após protocolos de corrida podem revelar uma baixa capacidade adaptativa ou de recuperação e identificar corredores em maior risco de ocorrência de lesão.

O movimento humano é resultado de interações não lineares entre os muitos elementos e sistemas (e.g., neuromuscular, cardiorrespiratório, fisiológico) que se auto-organizam para produzir comportamentos macroscópicos (e.g., movimentos coordenados

para completar uma tarefa) abrangendo vários níveis (e.g., coordenação intermuscular ou articular) (Garcia-Retortillo e Ivanov, 2022; Kelso e Schöner, 1988; Pol *et al.*, 2018; Turvey, 1990). A identificação de variáveis macroscópicas (i.e., parâmetros de ordem) capazes de caracterizar estados fisiológicos distintos (e.g., fadiga ou lesão) é desafiador, mas fundamental para investigar como o movimento evolui e se adapta em resposta a perturbações, como exercício e fadiga (Fonseca *et al.*, 2020). Dessa forma, mudanças no estado de um indivíduo podem ser precedidas de alterações no comportamento de variáveis que representem o estado geral do sistema (Coffey, 1998; Emmerik, van *et al.*, 2016; Fonseca *et al.*, 2020; Haken, 1980; Hamill, Palmer e Emmerik, Van, 2012; Kelso, Scholz e Schöner, 1986). Embora variáveis de desempenho (e.g., número de repetições), biomecânicas (e.g., força e atividade muscular) e fisiológicas (e.g., $\text{VO}_2\text{máx}$) sejam comumente usadas como marcadores para determinar a influência do exercício no risco de lesão, elas fornecem informações insuficientes sobre as interações entre os sistemas biológicos (Ceyssens *et al.*, 2019; Garcia-Retortillo e Ivanov, 2022; Peterson *et al.*, 2022). Considerando que o movimento emergente influencia no comportamento e as interações entre as partes (e.g., articulações), as mudanças tempo-dependentes no padrão ou estrutura do movimento (i.e., dinâmica do movimento) podem fornecer informações sobre o estado fisiológico do indivíduo. Portanto, ao invés de medir fatores individuais relacionados ao risco de lesão, examinar as mudanças de variáveis que refletem a dinâmica do movimento em resposta ao exercício ou fadiga poderiam fornecer mais informações sobre o estado do corredor (e.g., presença de fadiga e recuperação insuficiente ou lesão) (Fonseca *et al.*, 2020).

Maior parte dos estudos investigando mudanças no padrões de movimento em reposta ao exercício analisaram variáveis discretas (i.e., média, picos, curvas médias normalizadas), que podem caracterizar a tarefa, mas podem não fornecer informações suficientes sobre a estrutura do movimento observado (Preatoni *et al.*, 2013; Stergiou e Decker, 2011). Variáveis discretas são geralmente analisadas por meio de análises lineares que consideram ciclos/repetições como eventos semelhantes, mas independentes, que precisam ser resumidos por meio de estatísticas (e.g., comportamento médio e intervalos de confiança) (Preatoni *et al.*, 2013). Embora as análises lineares produzam informações úteis e fáceis de calcular e interpretar, elas não consideram as mudanças tempo-dependentes na estrutura do movimento (Preatoni *et al.*, 2013; Stergiou e Decker, 2011). Consequentemente, resultados inconsistentes foram reportados quando as médias de váriaveis cinemáticas e de padrões coordenativos foram investigadas após a corrida (Dal Pupo *et al.*, 2017; Estep *et al.*, 2018; Riazati *et al.*, 2020). Em contraste, análises não lineares vem sendo utilizadas por considerarem os ciclos de movimento como eventos interdependentes em uma série temporal contínua e avaliam

dinamicamente as mudanças que ocorrem em cada ciclo (Preatoni *et al.*, 2013). Por exemplo, medidas não lineares (e.g., entropia) demonstraram ser mais sensíveis do que medidas cinemáticas discretas (e.g., média dos ângulos articulares normalizados) na detecção de diferenças após protocolos de treinamento e fadiga (Estep *et al.*, 2018; Hollman *et al.*, 2020). Dessa forma, a aplicação de ferramentas e conceitos de sistemas dinâmicos e complexos poderia melhorar o entendimento das alterações do movimento em resposta ao exercício e auxiliar na previsão de lesões (Fonseca *et al.*, 2020).

Para obter informações sobre a dinâmica do movimento após exercício e fadiga, ângulos articulares e os ângulos de fase relativos articulares (i.e., coordenação articular) foram analisados com medidas não lineares, como a entropia (Carvalho *et al.*, 2023; Hollman *et al.*, 2020; Schütte *et al.*, 2015). Medidas de entropia quantificam o grau de incerteza ou irregularidade em uma série temporal (Richman e Moorman, 2000). Menores valores de entropia indicam maior regularidade, o que tem sido relacionado a comportamentos mais preditivos e menos adaptativos (Busa e Emmerik, Van, 2016). Estudos demonstraram que a entropia pode ser sensível ao aumento da demanda da atividade, mas os resultados são inconclusivos. Após protocolos de fadiga, diminuições (Carvalho *et al.*, 2023; Schütte *et al.*, 2018), aumentos (McGregor *et al.*, 2009, 2011; Murray *et al.*, 2017; Schütte *et al.*, 2015), ou ausência de diferenças (Bauer *et al.*, 2017) foram observados na regularidade da aceleração segmentar, deslocamento angular articular, e centro de massa corporal. A entropia também foi capaz de diferenciar indivíduos com menor capacidade adaptativa (i.e., lesão, patologia ou idosos) de indivíduos jovens e saudáveis. Por exemplo, maior regularidade (i.e., menor entropia) vem sendo observada em indivíduos lesionados ou com histórico de lesões, comparado com indivíduos sem lesão (Kiefer *et al.*, 2013; Quirino *et al.*, 2021; Schütte *et al.*, 2018; Terada *et al.*, 2015; Tochigi *et al.*, 2012). Poucos estudos investigaram a entropia de padrões coordenativos do movimento. Apesar de nenhuma diferença ter sido observada na entropia de joelho-quadril após um protocolo de esforço máximo em indivíduos saudáveis (Hollman *et al.*, 2020), maior regularidade da coordenação tornozelo-quadril foi observada em atletas lesionados em comparação com não lesionados (Kiefer *et al.*, 2013). Portanto, avaliar mudanças induzidas pelo exercício na dinâmica do movimento podem distinguir corredores com capacidade adaptativa reduzida e indicar lesão iminente. Porém, é necessário esclarecer a influência do exercício e do tempo de recuperação na regularidade articular e coordenativa, e melhorar a compreensão dos mecanismos de *overtraining* relacionados com lesões por *overuse*.

A recuperação é um processo relativo ao tempo de reparação dos vários sistemas biológicos para restabelecer ou exceder a capacidade funcional existente (Bishop, Jones e Woods, 2008; Kellmann *et al.*, 2018). Durante o processo de recuperação, aspectos fisiológicos, psicológicos, sociais e ambientais podem afetar e serem afetados por fatores internos e externos ao indivíduo (Kallus e Kellmann, 2016; Kellmann *et al.*, 2018). Em geral, quanto maior o nível de estresse imposto sobre o sistema, maior a necessidade de recuperação (Kellmann e Beckmann, 2017). Corredores comumente variam a intensidade das sessões de treinamento (i.e., intensidades moderada e alta) (García-Pinillos, Soto-Hermoso e Latorre-Román, 2017; Laursen e Jenkins, 2002), o que pode levar a vários níveis de fadiga e demandar diferentes tempos de recuperação (Dierks, Davis e Hamill, 2010; Kellmann *et al.*, 2018; Monjo, Terrier e Forestier, 2015). As lesões relacionadas à corrida estão relacionadas à diminuição da capacidade de adaptação aos estresses repetidamente impostos ao longo do tempo (Hreljac, 2005). Dessa forma, períodos contínuos de recuperação insuficientes para demanda imposta podem ultrapassar a capacidade de adaptação dos diversos tecidos e sistemas, contribuindo para o desenvolvimento de lesões (Kellmann *et al.*, 2018; Kellmann e Beckmann, 2017; Soligard *et al.*, 2016). Além disso, o mesmo exercício que pode induzir mudanças em um grupo (e.g., indivíduos propensos a lesões) pode não alterar a dinâmica do movimento em outro grupo (e.g., não lesionados). Portanto, apesar de o tempo de recuperação após uma atividade física ser individual e contexto-dependente (Kellmann e Beckmann, 2017; Thomas *et al.*, 2018), alterações imediatas ou prolongadas nos padrões de movimento após protocolos de corrida em diferentes intensidades podem revelar uma capacidade de adaptação ou recuperação reduzida, e distinguir grupos de corredores com maior risco de sofrer lesões. Dessa forma, a avaliação da estrutura de movimento de um indivíduo durante a execução de atividades ou tarefas contínuas pode fornecer informações sobre como este indivíduo responde ao exercício.

O agachamento é a base para muitas tarefas relacionadas ao esporte, como saltar e correr, e é comumente usado como parte de sessões de treinamento e reabilitação (Bittencourt *et al.*, 2012; Cardoso *et al.*, 2021; King e Hannan, 2019; Rees, Younis e MacRae, 2019; Ugalde *et al.*, 2015). O agachamento unipodal é uma tarefa funcional que simula atividades da vida diária (e.g., subir e descer escadas) e atividades esportivas, que requer coordenação entre as articulações do tornozelo, joelho e quadril para manter o equilíbrio sobre uma base de apoio reduzida (Bittencourt *et al.*, 2012; Ksoll *et al.*, 2022). A tarefa de agachamento unipodal tem sido utilizada para informar sobre a condição física dos atletas, como avaliação do risco de lesão e retorno ao esporte, e distinguir participantes com e sem lesões (Cardoso *et al.*, 2021; Petushek *et al.*, 2021; Ugalde *et al.*, 2015). Embora a cinemática do agachamento

unipodal (e.g., ângulos articulares) seja comumente investigada, pouco foi investigado a respeito das mudanças nos padrões coordenativos após o treinamento ou na presença de fadiga. Além disso, a maioria dos estudos avaliou variáveis de desempenho (e.g., número de repetições, tempo e velocidade) e biomecânicas (e.g., pico de valgo do joelho) do agachamento unipodal a partir de um pequeno número de repetições (Bittencourt *et al.*, 2012; Cardoso *et al.*, 2021; Ksoll *et al.*, 2022). Porém, atividades esportivas impõem demandas cíclicas sobre o indivíduo e a mesma tarefa pode ser realizada de maneiras diferentes (Latash, 2012). Portanto, variáveis que descrevam a estrutura do movimento durante períodos mais longos (mais ciclos) são necessárias para investigar a influência da intensidade do treinamento na dinâmica do movimento. Assim, essa tarefa é uma candidata em potencial para ser utilizada como forma de rastreamento para avaliar mudanças na dinâmica do movimento após a realização de treinamentos e exercícios.

Para ser capaz de prever lesões futuras, é necessário identificar variáveis de alta ordem que caracterizem estado do sistema (e.g., regularidade articular e coordenativa durante uma tarefa funcional), estabelecer protocolos para capturar a evolução temporal do parâmetro de ordem (mudanças imediatas e prolongadas após protocolos de corrida em diferentes intensidades) e selecionar métodos adequados para analisar essa dinâmicas e prever estados futuros (i.e., medidas de entropia) (Fonseca *et al.*, 2020). Correr em diferentes intensidades pode levar à fadiga e mudanças nos padrões de movimento, que podem ser capturados por mudanças na regularidade das articulações e do padrão coordenativo durante a execução de agachamentos unipodais contínuos. Sendo assim, como a corrida e o tempo de recuperação podem afetar o padrão coordenativo durante o agachamento unipodal, este estudo pode ser um passo inicial para identificar indivíduos que apresentam menor capacidade de adaptação e recuperação em resposta a demandas impostas pelo exercício. Portanto, o objetivo principal do presente estudo foi investigar a influência da intensidade da corrida e do tempo de recuperação na cinemática, o padrão coordenativo, e a regularidade dos membros inferiores durante uma tarefa de agachamentos unipodais e a relação das mudanças na regularidade com a ocorrência de lesões em praticantes de corrida.

2 OBJETIVOS E HIPÓTESES

2.1 Objetivo geral

Investigar a influência da intensidade da corrida e do tempo de recuperação após corrida na cinemática, o padrão coordenativo, e a regularidade dos membros inferiores durante a tarefa de agachamentos unipodais e a relação com a ocorrência de lesões em praticantes de corrida.

2.2 Objetivos específicos

2.2.1 Investigar o efeito imediato e prolongado da corrida em diferentes intensidades sobre a cinemática, padrão coordenativo e a regularidade dos membros inferiores durante a tarefa de agachamentos unipodais em praticantes de corrida (Estudo 1).

2.2.2 Investigar se o efeito da corrida em diferentes intensidades e do tempo de recuperação na regularidade articular e do padrão coordenativo durante a tarefa de agachamentos unipodais é capaz discriminar prospectivamente a ocorrência de lesão em praticantes de corrida (Estudo 2).

2.3 Hipóteses

2.3.1 A atividade física levará a um aumento imediato da regularidade articular (tornozelo, joelho e quadril no plano sagital) e do padrão coordenativo (acoplamento entre tornozelo e joelho e joelho e quadril no plano sagital) durante a tarefa de agachamentos unipodais de praticantes de corrida.

2.3.1.1 A regularidade articular (tornozelo, joelho e quadril no plano sagital) e do padrão coordenativo (acoplamento entre tornozelo e joelho e joelho e quadril no plano sagital) durante a tarefa de agachamentos unipodais permanecerá aumentada após 24h, mas retornará aos valores iniciais após 48h da atividade física em intensidade alta. A regularidade retornará aos valores iniciais 24h após a atividade em intensidade moderada.

2.3.1.2 O efeito da corrida em diferentes intensidades não será capturado pela análise de curvas médias (normalizadas pelo ciclo) da cinemática (tornozelo, joelho e quadril no plano sagital) e do padrão coordenativo (acoplamento entre tornozelo e joelho e joelho e quadril no plano sagital) durante a tarefa de agachamentos unipodais de praticantes de corrida.

2.3.1.3 Quanto maior a intensidade da corrida maior será a regularidade articular (tornozelo, joelho e quadril no plano sagital) e do padrão coordenativo

(acoplamento entre tornozelo e joelho e joelho e quadril no plano sagital) durante a tarefa de agachamentos unipodais de praticantes de corrida.

2.3.1.4 Nenhuma mudança será observada nas variáveis analisadas durante a tarefa de agachamentos unipodais na situação controle (descanso, sem atividade física).

2.3.2 Um aumento da regularidade articular (tornozelo e joelho no plano sagital) e do padrão coordenativo (acoplamento entre tornozelo e joelho no plano sagital) durante a tarefa de agachamentos unipodais será observada imediatamente após corrida em diferentes intensidades, e o aumento será maior em indivíduos que reportaram lesão em até seis meses após as avaliações.

2.3.2.1 Após o protocolo de maior intensidade de corrida, maior será o tempo de recuperação - tempo para a regularidade articular e o padrão coordenativo durante a tarefa de agachamentos unipodais retornar para os valores iniciais - da regularidade articular e coordenativa durante a tarefa de agachamentos unipodais para ambos os grupos.

2.3.2.2 O tempo de recuperação será maior em indivíduos que reportaram lesão em até seis meses após as avaliações, comparado com o grupo sem lesão.

2.3.2.3 Não haverá mudanças entre os grupos com e sem lesão no pré-teste ou na situação controle (a mudança na regularidade será induzida somente pelos protocolos de corrida).

3 MATERIAIS E MÉTODOS

3.1 Delineamento do estudo

O presente trabalho se trata de ensaio controlado aleatorizado do tipo crossover com follow-up de seis meses.

3.2 Amostra

Trinta e três indivíduos foram recrutados por conveniência na comunidade, baseados nos seguintes critérios de inclusão: (1) praticantes de corrida há pelo menos seis meses (2 a 4 vezes, média de 20 a 70 km por semana); (2) adultos com idade entre 18 e 60 anos; (3) sem lesão - dor musculoesquelética nos membros inferiores que cause restrição ou paralisação da atividade física (distância, velocidade, duração ou treinamento) por pelo menos 7 dias ou 3 sessões de treinamento agendadas consecutivas, ou que necessite de consulta um médico ou outro profissional de saúde (Yamato, Saragiotto e Lopes, 2015). Foram excluídos os indivíduos que: (1) não fossem capazes de completar os protocolos de corrida nas intensidades determinadas; (2) falhassem em seguir as orientações dos pesquisadores no período entre avaliações; (3) não comparecer nas reavaliações; (4) apresentassem queixa de dor e/ou lesão durante a pesquisa. Dois indivíduos foram excluídos do estudo, um por não comparecer às reavaliações e outro por queixa de dor/lesão no período das avaliações. Um terceiro participante foi excluído do estudo por falhas no sistema durante um dia de coleta de dados, ocasionando a perda da reavaliação.

Todos os participantes foram orientados a manter a rotina de treinos (intensidade, volume e pace médio) que estavam realizando até que seja finalizado todas as etapas e avaliações. As coletas foram realizadas no Laboratório de Análise do Movimento (LAM) e no Centro de Treinamento Esportivo (CTE) da UFMG. Todos os participantes foram orientados sobre o estudo e assinaram o Termo de Consentimento Livre e Esclarecido aprovado pelo Comitê de Ética da Universidade (CAAE: 39729120.2.0000.5149).

3.3 Procedimentos

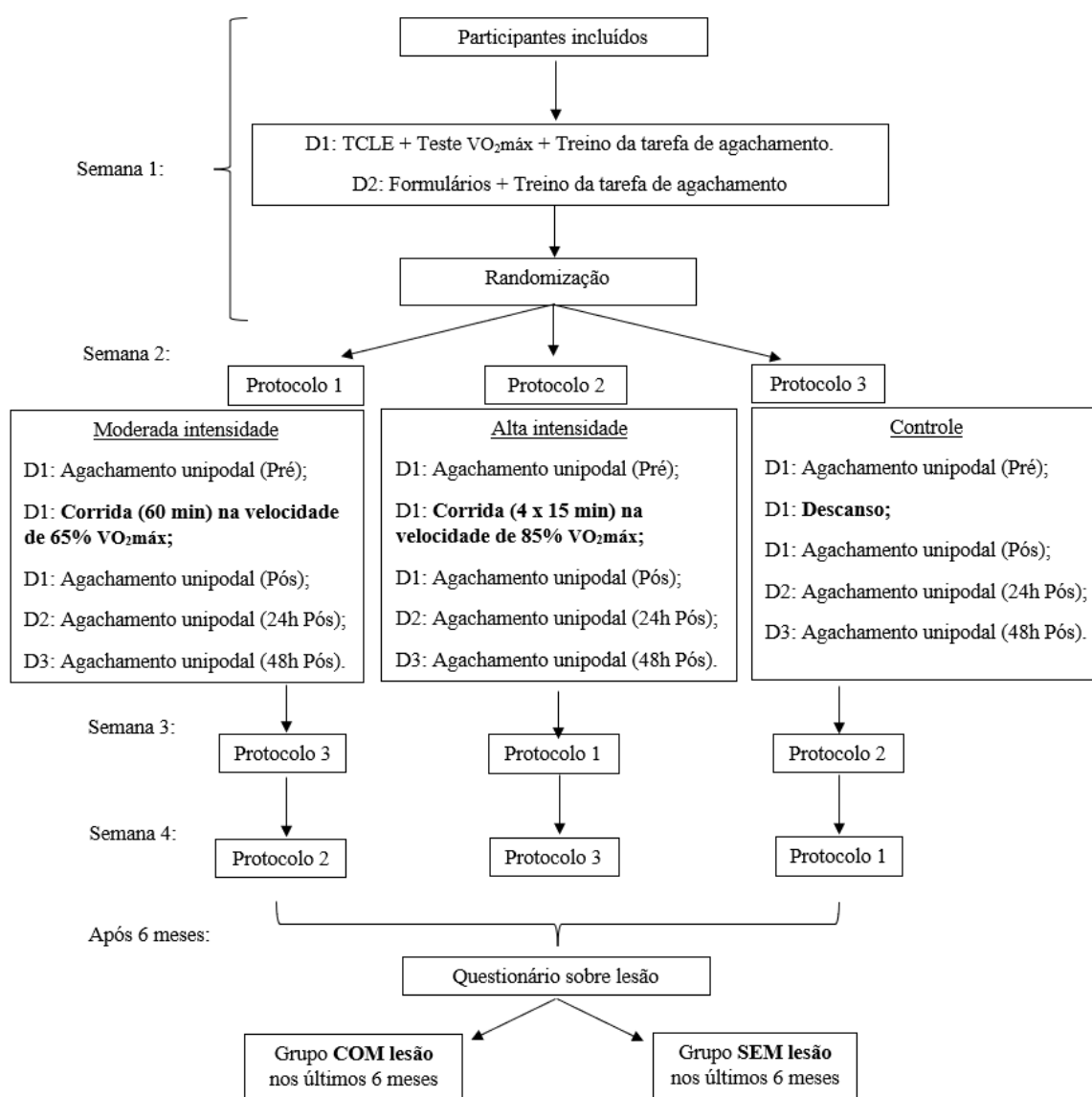
Os participantes foram avaliados por 4 semanas. Na primeira semana, duas visitas foram necessárias para realizar o teste de VO_{2max} e treino da tarefa de agachamento unipodal. Um estudo piloto com 10 participantes indicou que dois dias de treinamento eram necessários para minimizar efeitos do aprendizado da tarefa. Os dados do estudo piloto foram utilizados para calcular a confiabilidade entropia da fase relativa entre tornozelo e joelho, e joelho e quadril no plano sagital. Os resultados revelaram que a confiabilidade variou de alta

a excelente ($ICC_{3,3}$: 0,81 – 0,91) (Portney e Watkins, 2015). Além disso, os participantes preencheram um questionário informando sua rotina de treinamento, tempo de prática contínua da corrida, volume médio de treino semanal no último mês, pace médio, atividade física adicionais (e.g., musculação) e histórico de lesões nos últimos 6 meses.

Nas três semanas seguintes, três dias consecutivos de avaliação foram realizadas a cada semana. No primeiro dia de avaliação de cada semana, eram realizados o protocolo de atividade física (intensidade moderada, intensidade alta ou controle) e dois testes de agachamento unipodal (antes e depois do protocolo selecionado). No segundo (24h após protocolo) e terceiro (48h após protocolo) dias, os participantes realizavam um teste de agachamento unipodal. Todos os participantes foram submetidos a três protocolos de atividade física – corrida em intensidade moderada, corrida em alta intensidade e controle (nenhuma atividade física). A ordem de realização dos protocolos foi aleatória, por sorteio. Um fluxograma com a sequência das atividades e os protocolos realizados é apresentado na Figura 1.

Após seis meses do término das avaliações, os participantes responderam a um questionário online informando a ocorrência de lesões após finalizarem a participação na pesquisa. Todos os participantes foram informados e orientados sobre a definição de lesão utilizada (Yamato, Saragiotto e Lopes, 2015). Aqueles que reportaram lesão nos últimos seis meses, também informaram sobre o local e tipo de lesão, quando ocorreu, necessidade de consulta com profissional de saúde e tempo de afastamento ou redução das atividades físicas. A partir disso, os participantes foram divididos em dois grupos, com e sem lesão. Os corredores que reportaram lesão nos seis meses seguintes das avaliações foram pareados com corredores que não apresentaram lesão no mesmo período. O pareamento foi realizado de acordo com a idade, sexo, índice de massa corporal e VO_{2max} , tempo de prática, volume de treino semanal, pace e atividade física adicional.

Figura 1 - Fluxograma exemplificando o protocolo do estudo



Fluxograma exemplificando o protocolo do estudo durante as quatro semanas de avaliação e reavaliação em seis meses. Na Semana 1 foram realizados treinos da tarefa de agachamento unipodal, testes e formulários para caracterização da amostra e determinação dos parâmetros dos protocolos. A cada semana (Semanas 2 a 4), um protocolo era realizado na ordem definida por randomização. Todos os participantes realizaram cada um dos três protocolos (moderada intensidade, alta intensidade e controle). Seis meses após finalizaram todas as avaliações, os participantes responderam um questionário relatando se apresentaram ou não lesão nesse período. Os indivíduos que relataram ter tido lesão nos últimos seis meses, foram pareados com aqueles que não sofreram lesão no mesmo período. TCLE: Termo de Consentimento Livre e Esclarecido; VO₂máx: Volume máximo de oxigênio; D1: Primeiro dia de avaliação; D2: Segundo dia de avaliação; D3: terceiro dia de avaliação.

Fonte: do autor.

3.3.1 Agachamento unipodal

Para realizar a tarefa de agachamento unipodal os participantes foram solicitados a ficar descalço sobre a membro inferior dominante (i.e., membro inferior de preferência ao chutar uma bola), pé alinhado perpendicular a um painel localizado à frente, e as mãos cruzadas atrás da cabeça (Figura 2). O painel continha duas faixas/alvos horizontais, superior e inferior, separadas verticalmente à uma distância de 30 cm. Uma caneta laser foi fixada em uma estrutura rígida (cluster) posicionada na lateral da coxa dos participantes, dois dedos acima da patela, alinhado ao trocânter maior e paralelo ao solo. A altura do painel foi ajustada individualmente de forma que o laser apontasse para o centro da faixa inferior, com os participantes em apoio unipodal e joelho estendido. A tarefa utilizada foi adaptada do teste funcional proposto por Cardoso et al. (2021). Porém, os autores não normalizaram a amplitude de movimento entre participantes, o que pode ter imposto diferentes amplitudes e demandas para cada pessoa dependendo das características antropométricas do participante. Para lidar com essa limitação, o presente estudo normalizou a amplitude de movimento durante a tarefa.

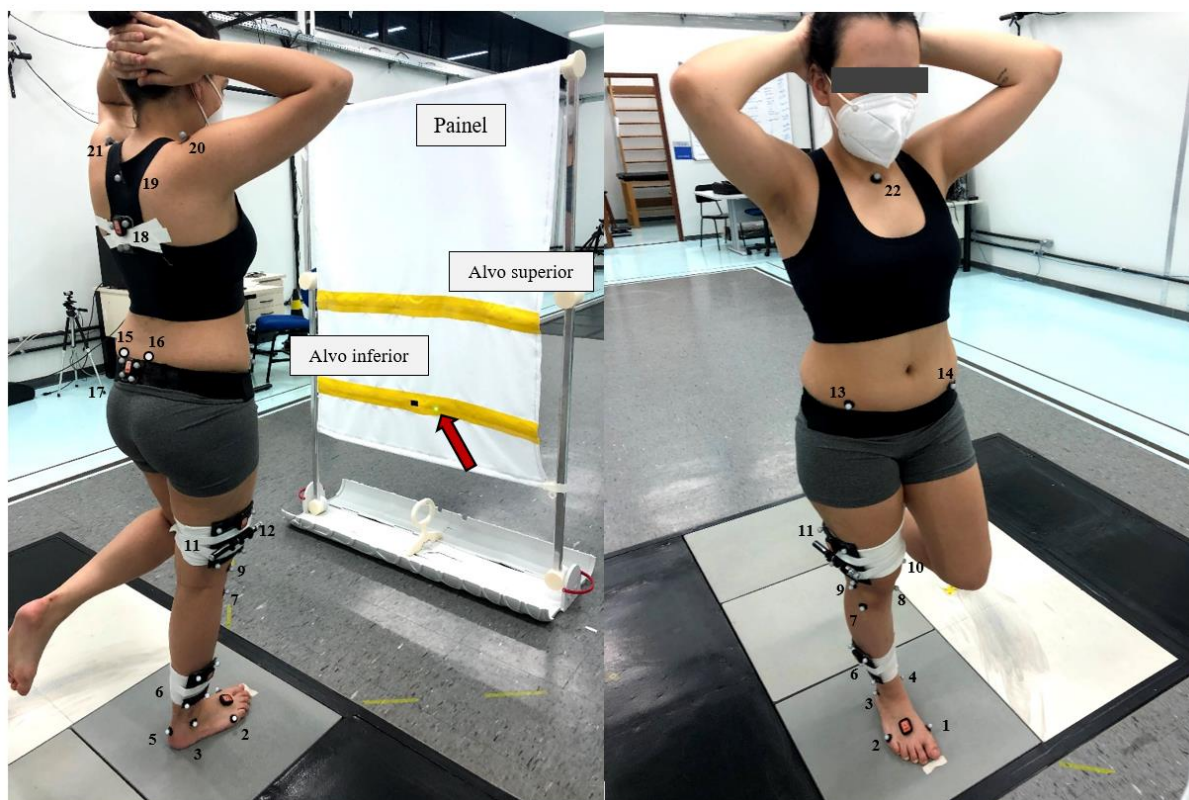
A distância de cada participante ao painel foi determinada de forma com que todos os indivíduos realizassem um mínimo de 40° de flexão de joelho durante cada ciclo do agachamento. Esta amplitude de movimento foi estabelecida a partir de pesquisas anteriores (Bittencourt *et al.*, 2012; Petushek *et al.*, 2021; Ugalde *et al.*, 2015) e do nosso estudo piloto. De acordo com estudos prévios, o pico de flexão de joelho foi utilizado para definir a amplitude de movimento durante a tarefa de agachamento unipodal, variando entre 30° e 90° de flexão de joelho (Bittencourt *et al.*, 2012; Cardoso *et al.*, 2021; Petushek *et al.*, 2021; Rees, Younis e MacRae, 2019; Ugalde *et al.*, 2015). Entretanto, esses estudos avaliaram apenas um número limitado de repetições (1 a 5 repetições). Para avaliar a dinâmica do movimento durante o agachamento unipodal a partir de análises não lineares (e.g., entropia) maior quantidade de dados e, conseqüente, maior número de repetições e tempo de duração do teste era necessário. O estudo piloto permitiu definir o tempo total de tarefa de 60 segundos para garantir que houvesse uma quantidade de dados suficiente para realizar as técnicas planejadas, minimizar o risco de exaustão do participante, e tornar a tarefa executável. Ainda durante o estudo piloto, observamos que a realização da tarefa com um pico de flexão do joelho igual ou maior que 50° levou à interrupção frequente dos testes (e.g., mover o pé e as mãos fora da posição) e fadiga induzida pela tarefa (i.e., aumento da percepção subjetiva de esforço geral e dos membros inferiores). Por outro lado, um pico de flexão do joelho de 30° foi muito fácil para os participantes. Isso nos levou a dividir a diferença e exigir 40° de flexão de pico do joelho para cada agachamento. Dessa forma, um

pico mínimo de 40° flexão tornou a tarefa desafiadora, mas viável para participantes fisicamente ativos realizarem agachamento unipodais ininterruptos por 60 segundos.

Para realizar a tarefa, os indivíduos deveriam realizar agachamentos unipodais ininterruptos durante 60 segundos, flexionando (laser apontado para o alvo superior) e estendendo (laser apontado para o alvo inferior) o membro inferior, mantendo o tronco ereto, e o pé contralateral fora do chão. Os comandos verbais utilizados foram: “Você deve agachar, levando o quadril para trás, dobrando o joelho, e tentando manter seu tronco ereto, para deslocar o laser do alvo inferior até o alvo superior, na sua velocidade de preferência, sem errar os alvos. Você pode ultrapassar os limites dos alvos, mas não pode retornar ao alvo inferior antes de tocar o alvo superior, e vice-versa”. A percepção subjetiva de esforço (PSE) foi avaliada antes e depois de cada teste (Borg, 1998), sendo as pontuações 0 e 10 correspondentes a nenhum esforço e esforço máximo, respectivamente. A tarefa era interrompida e repetida caso o participante encostasse o pé contralateral no membro de apoio ou no chão, retirasse as mãos de trás da cabeça, ou movimentasse o pé de apoio fora da posição inicial. Quando a repetição da tarefa era necessária, durante o pré-, 24h ou 48h pós-teste, os participantes descansavam por cinco minutos ou até retornarem ao PSE inicial. Caso necessitasse que a repetição acontecesse no pós-teste (intensidade moderada ou alta), nenhum descanso era oferecido, uma vez que já era esperado que os participantes apresentassem algum nível de fadiga em resposta ao protocolo de corrida. Como aquecimento, os participantes realizavam a tarefa por 30 segundos, exceto no pós-teste.

A cinemática durante a tarefa de agachamento unipodal foi analisada através de um sistema tridimensional de análise do movimento com 10 câmeras (Oqus, Qualisys Motion Capture System, Gotthenburg, Suécia) a uma frequência de 120 Hz. Foram rastreados os movimentos do pé, perna, coxa, pelve e tronco do voluntário, utilizando 33 marcadores refletivos (Figura 2) (Cappozzo *et al.*, 1995) (Wu *et al.*, 2002). Antes de cada tarefa de agachamento unipodal e após os protocolos de corrida, três coletas estáticas na posição ortostática. Somente o membro inferior dominante foi avaliado.

Figura 2 - Participante em posição inicial da tarefa de agachamento unipodal



Seta vermelha indica luz do laser apontando para alvo inferior. Modelo de marcadores para o sistema tridimensional de movimento no membro dominante. 1 - Cabeça do primeiro metatarso; 2 - Cabeça do quinto metatarso; 3 - Maléolo medial; 4 - Maléolo lateral; 5 - Calcâneo; 6- Cluster de rastreamento da perna; 7- Côndilo tibial lateral; 8- Côndilo tibial medial; 9- Epicôndilo femoral lateral; 10- Epicôndilo femoral medial; 11- Cluster de rastreamento da coxa; 12 - Laser posicionado no cluster da coxa; 13 e 14 - Espinhas ilíacas ântero superior direita e esquerda; 15 e 16 - Espinhas ilíacas pósterio superior direita e esquerda; 17 - Cluster de rastreamento da pelve; 18 - Cluster de rastreamento do tronco; 19 - Projeção da incisura jugular; 20 e 21 - Acrômios direito e esquerdo; 22 - Incisura jugular.

Fonte: do autor.

3.3.2 Teste de consumo máximo de oxigênio ($VO_{2\text{máx}}$)

O teste do $VO_{2\text{máx}}$ foi realizado com um espirômetro digital portátil (HandyMET Clinic, MDI, Brasil) durante um teste incremental de velocidade em esteira com inclinação fixa em 1% (Lourenço *et al.*, 2011). No dia do teste, os participantes eram orientados a não realizar nenhuma atividade física antes do teste de $VO_{2\text{máx}}$. Antes de iniciar o teste, os participantes foram familiarizados com a esteira, equipamento e protocolo, e realizavam um aquecimento de três minutos a uma velocidade de 8 km/h. O teste iniciou a velocidade de 9 km/h e, a cada 30 segundos, 0,5 km/h era incrementado até a exaustão do participante (Lourenço *et al.*, 2011). Após a exaustão do participante, a velocidade era reduzida em 60% da velocidade máxima, seguido de reduções de 5% a cada minute por cinco minutos (Lourenço *et al.*, 2011). O equipamento calculava a razão de troca respiratória (RER) a partir do volume de oxigênio consumido (VO_2) e o dióxido de carbono expirado (VCO_2). A

frequência cardíaca (FC) e a PSE eram mensuradas a cada minuto. O protocolo foi considerado um teste válido de $\text{VO}_2\text{máx}$ se dois ou mais critérios fossem atendidos ao final do teste: $\text{PSE} > 9$, $\text{FC} > 90\%$ dos 220 anos-idade, $\text{RER} > 1,1$, platô do VO_2 ou a pessoa não pudesse continuar (Cortes, Onate e Morrison, 2014; Quammen *et al.*, 2012). Todos os testes foram válidos, ou seja, todos os participantes tiveram seu $\text{VO}_2\text{máx}$ avaliado. O $\text{VO}_2\text{máx}$ foi estimado como o valor máximo de VO_2 observado durante o teste. A velocidade correspondente ao $\text{VO}_2\text{máx}$ durante o teste foi utilizado para determinar a intensidade do protocolo de corrida de cada participante (Billat, 2001; Encarnación-Martínez *et al.*, 2020; Kaufman *et al.*, 2006). Além disso, a FC máxima durante o teste foi utilizada para verificar a manutenção da intensidade durante os protocolos de corrida (Garber *et al.*, 2011; Kaufman *et al.*, 2006; Pollock *et al.*, 1998).

3.3.3 Protocolos

Todos os participantes realizaram os três protocolos de forma randomizada: corrida nas intensidades moderada e alta, e controle. Os protocolos de corrida foram realizados em uma esteira sem inclinação, enquanto nenhuma atividade era realizada no protocolo controle. Antes de cada protocolo de corrida os participantes realizavam a tarefa de agachamento unipodal (pré-teste) e um aquecimento na esteira por cinco minutos em velocidade auto selecionada. Imediatamente após, 24h e 48h após cada protocolo de corrida ou controle, os participantes realizavam a tarefa de agachamento unipodal (pós-teste, pós 24h, e pós 48h). A FC e a PSE eram avaliados a cada cinco minutos para garantir a intensidade do protocolo (Bellenger *et al.*, 2019; Garber *et al.*, 2011; Impellizzeri *et al.*, 2004; Kaufman *et al.*, 2006; Pollock *et al.*, 1998). Para minimizar os efeitos da atividade física nas variáveis analisadas, os participantes eram orientados a se absterem dos treinos nos dois dias anteriores de cada protocolo, inclusive o controle.

Para o protocolo em intensidade moderada, os participantes deveriam correr durante 60 minutos consecutivos a uma velocidade correspondente a 65% do $\text{VO}_2\text{máx}$ (Bellenger *et al.*, 2019; Pollock *et al.*, 1998; Powers e Howley, 2017). Durante o protocolo, a FC deveria permanecer entre 65 e 85% da FC máxima alcançada no teste de $\text{VO}_2\text{máx}$, e o PSE entre $6 \leq \text{PSE} < 8$ (Bellenger *et al.*, 2019; Pollock *et al.*, 1998; Powers e Howley, 2017). Já durante o protocolo de alta intensidade alta, o participante deveria correr quatro blocos de 15 minutos a uma velocidade correspondente a 85% do $\text{VO}_2\text{máx}$ (Bellenger *et al.*, 2019; Billat, 2001; Encarnación-Martínez *et al.*, 2020; García-Pérez *et al.*, 2014; Kaufman *et al.*, 2006; Pollock *et al.*, 1998). Entre cada bloco, os participantes descansavam em velocidade auto selecionada

por cinco minutos. A FC e PSE eram monitorados para garantir a manutenção da alta intensidade durante todo o protocolo (i.e., $\geq 85\%$ da FC máxima no teste de $\text{VO}_{2\text{máx}}$ e $\text{PSE} \geq 8$) (Garber *et al.*, 2011; Kaufman *et al.*, 2006; Pollock *et al.*, 1998). Nenhuma técnica de recuperação tecidual (e.g., crioterapia, massagem) poderia ser realizada entre o pré-teste e o teste 48h após os protocolos.

3.4 Análise dos dados

Dados cinemáticos do membro inferior dominante foram analisados durante a tarefa de agachamento unipodal e processados nos softwares Visual3D (C-Motion, Inc., Rockville, Maryland, USA) e MatLab (MathWorks Inc., USA). Um modelo biomecânico de corpos rígidos foi criado a partir da média das três coletas estáticas para computar o ponto zero de rotação de cada articulação e definir o sistema de coordenadas local. O deslocamento linear das marcas de rastreamento foram filtrados usando um filtro passa-baixa Butterworth de quarta ordem com a frequência de corte de 6Hz (Winter, 2009). Os ângulos articulares no plano sagital do membro inferior foram calculados: (1) tornozelo, representado pelo movimento do pé rígido em relação a perna; (2) joelho, representado pelo movimento da perna em relação a coxa (Portinaro *et al.*, 2014); (3) quadril, movimentos da coxa em relação a pelve. A sequência de Cardan utilizada foi: eixos médio-lateral; anteroposterior e longitudinal. Os ângulos do tornozelo, joelho e quadril foram analisadas em forma de séries temporais completas e curvas médias normalizadas pelo ciclo de agachamento. Mais detalhes sobre os passos seguintes no processamento e análise dos ângulos articulares são apresentados a seguir.

3.4.1 Ângulos articulares (normalizados pelo ciclo de agachamento)

Após o cálculo dos ângulos articulares, os eventos de início, meio e fim de cada agachamento foram definidos a partir dos picos de flexão e extensão do joelho. Especificamente, dois picos consecutivos de extensão do joelho determinaram um ciclo de agachamento unipodal e um meio ciclo correspondeu a um pico de flexão do joelho. Durante cada ciclo de agachamento, os ângulos do tornozelo, joelho e quadril no plano sagital foram normalizados para 101 pontos, onde os pontos 0, 50 e 101 corresponderam ao início, metade e fim do ciclo, respectivamente. As curvas médias normalizadas para cada ciclo durante cada tarefa de 60 segundos foram calculadas e extraídas usando o software Visual 3D. As curvas médias dos ângulos do tornozelo, joelho e quadril durante o agachamento unipodal para os ambos os protocolos de corrida (moderada e alta intensidades) e o protocolo de controle foram comparadas entre os períodos de avaliação (pré-teste, pós-teste, pós-24h e pós-48h).

Essa análise foi utilizada no Estudo 1.

3.4.2 Padrão coordenativo

A coordenação foi calculada pela medida de fase relativa contínua (CRP) (Hamill *et al.*, 1999; Lamb e Stöckl, 2014). A CRP quantifica a relação de fase entre dois segmentos corporais, gerando um novo sinal que representa a diferença nos ângulos de fase dos dois sinais originais (Lamb e Stöckl, 2014). Para determinar a fase relativa entre os segmentos/articulações, uma abordagem mais robusta para baseada na transformada de Hilbert foi utilizada (Lamb e Stöckl, 2014). A CRP baseada em Hilbert é uma análise menos sensível a ruídos e dados não senoidais, características comumente observadas em ângulos articulares (Emmerik, Van, Miller e Hamill, 2004; Hamill *et al.*, 1999).

A fase relativa gerada pela transformada de Hilbert é calculada com base no sinal medido $x(t)$ e sua transformada de Hilbert $H(t) = H(x(t))$ (Lamb e Stöckl, 2014). Esse procedimento permite a transformação de qualquer sinal real em um sinal analítico complexo, onde a transformada de Hilbert $H(t)$ de $x(t)$ é a parte imaginária do sinal analítico (Feldman, 2011; Lamb e Stöckl, 2014). Primeiro, a amplitude dos dados deve ser centrada em torno de zero (Eq.1) antes de calcular o sinal analítico usando a transformada de Hilbert baseada em $x_{centric}(t_i)$.

$$x_{centered}(t_i) = x(t_i) - \min(x(t)) - (\max(x(t)) - \min(x(t))) / 2 \quad (\text{Eq. 1})$$

Em seguida, o ângulo de fase no tempo $t(i)$ pode ser calculado para cada sinal (Eq. 2), e a CRP entre os dois sinais é calculada subtraindo-se os ângulos de fase um do outro (Eq.3)

$$\phi(t_i) = \arctan(H(t_i) / x(t_i)). \quad (\text{Eq. 2})$$

$$\text{CRP}(t_i) = \phi_1(t_i) - \phi_2(t_i) \quad (\text{Eq. 3})$$

Como resultado se tem uma nova série temporal com valores variando de 0° a 180° (em fase e anti-fase, respectivamente). Quando os dois segmentos estão em fase, ambos estão coordenados, movendo-se na mesma direção, enquanto na coordenação anti-fase, os segmentos se movem em direções opostas.

Para o Estudo 1, as curvas normalizadas do tornozelo, joelho e quadril no plano sagital foram utilizadas para calcular a coordenação articular. A CRP calculou os ângulos de fase relativa entre tornozelo-joelho e joelho-quadril no plano sagital e as médias das curvas

foram comparadas entre os períodos de avaliação para todos os protocolos.

Além disso, a CRP baseada na transformada de Hilbert foi calculada a partir das séries temporais completas, sem normalização por ciclo, dos deslocamentos angulares de tornozelo, joelho e quadril no plano sagital. Para o Estudo 1, o acoplamento entre tornozelo-joelho e joelho-quadril foram calculados e utilizadas no cálculo de entropia. Já para o Estudo 2, somente o acoplamento entre tornozelo-joelho no plano sagital foi calculado e utilizado na análise de entropia.

3.4.3 Regularidade articular e dos padrões coordenativos

A regularidade das articulações (tornozelo, joelho e quadril) e dos padrões coordenativos (i.e., ângulos de fase relativa entre tornozelo-joelho e joelho-quadril) foi calculada usando a Entropia *Multiscale* (MSE). O MSE estima o grau de aleatoriedade de uma série temporal em múltiplas escalas temporais (τ) usando um procedimento de *coarse-graining* (Costa, Goldberger e Peng, 2002). Em cada escala temporal, a entropia é determinada usando o método de Entropia Amostral (SampEn). Para a escala um, a MSE calcula a SampEn da série temporal original. O procedimento de *coarse-graining* divide a série temporal original em janelas não sobrepostas, faz médias sucessivas dos pontos de dados consecutivos em uma nova série temporal *coarse-grained*, e calcula a SampEn para cada uma dessas séries temporais (Costa, Goldberger e Peng, 2002).

SampEn é o logaritmo natural negativo da probabilidade condicional de que duas sequências de pontos de dados m que estejam próximas dentro de uma tolerância r permaneçam próximas quando as sequências são aumentadas para $m + 1$ pontos de dados (Richman e Moorman, 2000). Para selecionar os valores dos hiperparâmetros m (tamanho da sequência de pontos) e r (raio de similaridade), foram adaptados os critérios sugeridos por Ramdani et al. (2009). O valor mediano de SampEn e o erro padrão das estimativas de SampEn em todas as séries temporais de articulação e coordenação foram calculados, com $.05 < r < 1$ em passos de .05 e $m = 2, 3, 4, 5$ (material suplementar, Estudo 1). Adicionalmente, para avaliar o ponto de convergência e maximizar a precisão das estimativas de SampEn, a variância de SampEn para diferentes valores de m em relação à média foi calculada, assim como a porcentagem do erro padrão em relação às estimativas de SampEn em cada valor de r . O hiperparâmetro r selecionado foi aquele de menor variância e porcentagem de erro, sugerindo convergência das curvas naquele raio de similaridade (r) e menor erro da medida. Dessa forma, os hiperparâmetros selecionados e aplicados em todas as variáveis e escalas temporais foram $m = 2$ e $r = .20$. O comprimento de cada série temporal *coarse-grained* foi

determinada pelo quociente entre o comprimento da série temporal original (≈ 7200 pontos) e o número de escalas ($\tau = 35$), de forma que a menor série temporal deveria ter pelo menos 200 pontos (14^m com $m = 2$) (Gow *et al.*, 2015).

Para a análise de MSE foi necessário filtrar as séries temporais devido às tendências gerais não estacionárias, e desvios de baixa frequência das curvas que podem superestimar os valores de entropia (Gow *et al.*, 2015). A menor frequência (f_L) que deveria ser incluída na análise do MSE foi determinada com base no tamanho, duração da série temporal em segundos (t), no número de pontos na última escala (N_{Tm}) e no hiperparâmetro m (Eq. 4) (Gow *et al.*, 2015). Portanto, as séries temporais de tornozelo, joelho e quadril foram filtradas com filtro passa-alta e ponto de corte de 0,5 Hz. A série temporal articular filtrada foi utilizada para calcular a CRP do tornozelo-joelho e joelho-quadril no plano sagital antes de calcular a entropia. A análise de MSE foi então utilizada para calcular a regularidade dos ângulos articulares e dos padrões de coordenativos filtrados.

$$f_L = N_{Tm} / 2 \times (m + 1) \times t \quad (\text{Eq. 4})$$

A área debaixo da curva de SampEn em múltiplas escalas é calculado (i.e., MSE index) e utilizado para informar sobre a regularidade das séries temporais analisadas. Durante o teste de agachamento unipodal, o MSE index dos deslocamentos de tornozelo, joelho e quadril, juntamente com a coordenação entre tornozelo-joelho e joelho-quadril foram comparados entre os períodos de avaliação para os três protocolos. Maior valor de MSE index (i.e., maior entropia) está relacionado a uma maior aleatoriedade do movimento ou maior incerteza sobre o comportamento futuro. Enquanto um valor de entropia mais baixo (i.e., menor MSE index) indica uma dinâmica mais regular ou um comportamento mais previsível (Costa, Goldberger e Peng, 2002; Gow *et al.*, 2015). Para o Estudo 1, o MSE index dos ângulos de tornozelo, joelho e quadril, e tornozelo-joelho e joelho-quadril foram calculados e comparados entre períodos de avaliações e protocolos. Enquanto que no Estudo 2, o MSE index do tornozelo, joelho e tornozelo-joelho foram comparados entre períodos de avaliações, protocolos e grupos.

3.5 Análise estatística, resultados e discussão

As análises estatísticas correspondentes as hipóteses levantadas e referentes a cada estudo estão descritas e detalhadas individualmente nos Estudos 1 e 2. Da mesma forma, os resultados e discussão de cada uma das análises foram descritas separadamente nos manuscritos abaixo, correspondentes aos Estudos 1 e 2.

4 ESTUDO 1

To be submitted to the Journal of Biomechanics

Article Type: Original Article

The immediate and prolonged effects of different running intensities on the regularity of joint and coordinative patterns in recreational runners.

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Abstract

Background: Insufficient recovery time relative to the exercise's demand is commonly experienced by runners and may increase the injury risk. Training and exercises can induce fatigue and altered movement patterns, which may best be assessed by examining the underlying dynamics of the movement structure during a sports-related task. This study investigated the immediate and prolonged effects of running at different intensities on lower-limb kinematics, coordinative patterns, and regularity during a single-leg squat task in runners. **Methods:** A 60-second single-leg squat task was used to evaluate the acute and prolonged effect of running protocols of different intensities in 30 healthy recreational runners. Lower-limb joints (ankle, knee, hip) and coordination (ankle-knee and knee-hip continuous relative phase) angles were analyzed by cycle-normalized curves and by the regularity (Multiscale entropy) of entire time-series. A Statistical Parametric Mapping one-way repeated measures ANOVA investigated the difference between Times (pre, post, post24h, post48h) in each protocol (moderate- and high-intensity run, control). Additionally, a two-way ANOVA calculated the interaction between Times and Protocols. **Results:** Increased ankle-knee regularity (lower entropy) was observed immediately after both running protocols (moderate-intensity, -17.6%; high-intensity, 18.6%), with no differences observed in 24h or 48h. However, lower entropy of the ankle and knee were observed at post48h. No differences were observed for pre-test values or joint and coordination angles normalized by squat-cycle. **Discussion:** Runners demonstrated more regular ankle-knee coordination after running protocols. In addition, increased regularity was also observed on joint angles 48h after protocols, suggesting an ongoing recovery process. The analysis of cycle-normalized kinematics curves was not sensitive to detect the effect of running on movement patterns. The approach adopted is a starting point for understanding the exercise-induced responses and recovery time after running. Future studies should continue investigating joint and coordination regularity changes and their relationship with injury occurrence.

Keywords: Fatigue; Recovery; Ankle; Knee; Hip; Sample entropy; Relative-phase.

Introduction

Different intensities of exercise lead to varying levels of fatigue that commonly impact movement patterns and demand time to recover (Dierks et al., 2010; Kellmann et al., 2018; Monjo et al., 2015). Changes in joint angles, coordination patterns, and regularity can be observed after exercise, even in the absence of exhaustion or maximal fatigue (Dierks et al., 2010; Mo and Chow, 2019; Quirino et al., 2021; Riazati et al., 2020; Santos et al., 2023). Consequently, an imbalance between the activity demand and recovery time can increase the injury risk (Kellmann et al., 2018; Soligard et al., 2016). For example, runners experience high rates of overuse injuries (Buist et al., 2010; Messier et al., 2018; Van Gent et al., 2007; Videbæk et al., 2015), which are related to fatigue, training load, and improper recovery (Hreljac, 2004; Soligard et al., 2016). However, there is still an absence of a clear understanding of the effect of exercise and fatigue on movement patterns (Bishop et al., 2008). For instance, most studies have evaluated the immediate effects of exercise that induce maximal effort or mechanical failure without considering a prolonged effect (Hollman et al., 2020; Möhler et al., 2021; Smith et al., 2021; Stock et al., 2016). Since overtraining syndrome is commonly experienced in runners (Meeusen et al., 2013), investigating the immediate and prolonged effect of running intensity on movement patterns can help to uncover the processes related to the individual responses to exercise, recovery time, and injury-related mechanisms.

Functional movement patterns result from coordinated interactions between many neural, muscular, and metabolic components organized temporally on different time scales (Kelso and Schöner, 1988; Turvey, 1990). Movement coordination can be defined as the mastering of the many available degrees of freedom involved in a particular movement (Bernstein, 1967) and is commonly quantified by the phase relationship between two segments/joints with relative phase analyses, such as continuous relative phase (Hamill et al., 1999; Lamb and Stöckl, 2014). The formation of coordinative structures reduces the number of independent variables to be controlled and enables the individual to produce different solutions for the same task (Bernstein, 1967; Kelso and Schöner, 1988; Turvey, 1990). Individuals with more flexible and adaptable behavior optimize their task performance (Latash, 2012). In contrast, individuals with reduced capacity (e.g., injured, diseased, or aged) tend to adopt more regular and less adaptative coordination patterns following perturbations (Kiefer et al., 2013; Paterno et al., 2015; Santos et al., 2023). Moreover, altered movement coordination patterns increase the risk of injuries (e.g., knee anterior cruciate ligament injury) (Hashemi et al., 2011; Paterno et al., 2015; Stock et al., 2016). Therefore, evaluating how joints interact and are coordinated to perform a task may provide more comprehensive

information about the movement pattern adopted in response to exercise, fatigue, and recovery than the analysis of joint kinematics alone (Hamill et al., 2012).

Studies investigating the influence of fatigue and recovery observed prolonged consequences on the musculoskeletal system (e.g., increase in creatine kinase and lactate concentration, decrease in muscle strength and performance, and kinematics changes) that persist up to 48h after the execution of activities inducing maximal effort or mechanical failure (Clermont et al., 2020; Martínez-Navarro et al., 2021; Thomas et al., 2018). However, these studies only analyzed discrete variables (i.e., mean, peaks, normalized mean curves), which can characterize a motor task but may not provide sufficient information on the observed movement (Preatoni et al., 2013; Stergiou and Decker, 2011). Discrete variables are analyzed through linear methods that consider subsequent cycles/repetitions as similar but independent events that need to be summarized through statistics (e.g., average patterns and confidence intervals) (Preatoni et al., 2013). While linear methods produce useful information that is easy to generate and interpret, they do not account for time-dependent changes in the pattern or structure of the behavior (Preatoni et al., 2013; Stergiou and Decker, 2011). Consequently, inconsistent results have been reported when average kinematics and coordination variables were investigated after running (Dal Pupo et al., 2017; Estep et al., 2018; Riazati et al., 2020).

Contrary to classical approaches, nonlinear analysis considers movement cycles as interdependent events in a continuous time-series and attempts to evaluate the underlying dynamics that govern the changes occurring within the cycles (Preatoni et al., 2013). For instance, nonlinear measures (e.g., entropy) have been demonstrated to be more sensitive than discrete kinematic measures (e.g., normalized mean joint angles) in detecting differences following training and fatigue protocols (Estep et al., 2018; Hollman et al., 2020). Entropy measures quantify the randomness or uncertainty in a time series (Richman and Moorman, 2000). Lower entropy values indicate greater regularity, which has been related to a less adaptable behavior (Busa and van Emmerik, 2016). Previous studies have demonstrated that entropy can be sensitive to increased activity demand, but the results are inconclusive. After the implementation of fatigue protocols, decreases (Carvalho et al., 2023; Schütte et al., 2018), increases (McGregor et al., 2011, 2009; Murray et al., 2017; Schütte et al., 2015), or no differences (Bauer et al., 2017) on the regularity of segment acceleration, joint angular displacement, and body center of mass have been reported. Additionally, only a few studies have investigated the entropy of movement coordination. Although no differences were observed in joint coordination entropy after a maximal effort protocol (Hollman et al., 2020), a more regular lower limb coordination pattern was observed in injured athletes compared to

non-injured athletes (Kiefer et al., 2013). Thus, more investigation is needed to clarify the influence of exercise and recovery time on joint and coordination regularity and to understand overtraining mechanisms related to overuse injuries.

Squat movements are the foundation for many sports-related tasks and are commonly used in training, assessment, and rehabilitation environments (Bittencourt et al., 2012; Cardoso et al., 2021; King and Hannan, 2019; Rees et al., 2019; Ugalde et al., 2015). The single-leg squat is a functional test that simulates activities of daily living (i.e., ascending and descending stairs) and sporting activities, such as jumping and running (Ksoll et al., 2022). Although the single-leg squat kinematic (e.g., joint angles) is commonly investigated, we do not have a detailed understanding of changes in coordination patterns after training or in the presence of fatigue. Additionally, most studies have evaluated only a small number of repetitions of the single-leg squat test (Bittencourt et al., 2012; Cardoso et al., 2021; Ksoll et al., 2022; Rees et al., 2019), which does not impose the cyclical demand of the sports activities and may not provide enough information about the influence of training intensity on movement pattern. Thus, this task is an interesting candidate to be used to assess changes in movement dynamics after the performance of training and exercises.

Running at different intensities can lead to fatigue and altered movement patterns, which might be captured by changes in the underlying dynamics of joints and coordination regularity during a sports-related task. This study investigated the immediate and prolonged effects of running at different intensities on lower-limb kinematics, coordinative patterns, and regularity during a 60-second single-leg squat test in recreational runners. We hypothesized joint and relative phase (i.e., coordination) mean angles normalized by the squat cycle would not change after the running protocols. We also predicted that the joints and coordination entropy during the single-leg squat test would immediately decrease (i.e., increased regularity) after running at different intensities, with the coordination regularity being more affected than the joint regularity. In general, the higher the running intensity imposed, the greater the impact of an activity on the system and the recovery time (Kellmann and Beckmann, 2017; Riazati et al., 2020). Thus, we expected that a higher-intensity running protocol would produce a greater increase in regularity than a moderate-intensity protocol. Additionally, regularity was expected to return to baseline values 24 hours after running at moderate intensity. Still, regularity would remain increased at 24 hours following the high-intensity run and only recover after 48 hours. In contrast, no differences in the outcome variables will be observed when the individuals are not exposed to any running protocol (i.e., control condition).

Methods

Participants

Recreational runners included in this crossover experimental study were adults between 18 and 60 years of age who regularly ran at least 20 km/week for at least six months. Participants could not present injuries, defined as musculoskeletal pain or discomfort resulting in reduced or restricted training volume for seven days or three consecutive training sessions, or require professional health care assistance (Yamato et al., 2015). Exclusion criteria were as follows: (1) inability to complete the running protocols or the single-leg squat test, (2) failure to follow the instructions during the evaluation periods, (3) failure to attend all assessments, and (4) pain or discomfort during the study. Two participants were excluded from the study because of their unavailability to continue attending the assessment, and the other presented with pain during the evaluation period. A third runner completed the study but was excluded because of data loss. The runners were instructed to maintain their previous month's training routine (volume, pace, and intensity) until the end of the study. All participants were instructed about the study and signed a Consent Form approved by the University's Ethics Committee (CAAE: 39729120.2.000.5149).

Procedures

The study consisted of four weeks of evaluation. In the first week, two days were needed to estimate the maximum oxygen volume consumed ($\text{VO}_{2\text{max}}$), practice the single-leg squat test, and complete the sample characterization forms. According to our pilot data, two days of practice were necessary to minimize the learning effects of the single-leg squat test. Participants reported their training routine, average pace and volume, running experience, additional physical activity (e.g., strength training), and previous injuries in the past six months. Over the following three weeks, three days of assessment were performed. On the first day, participants completed the single-leg squat test before and after three protocols: moderate- and high-intensity run and control (no exercise). After each protocol, the single-leg squat test was repeated in 24h (second day) and 48h (third day). All participants completed all protocols, one per week, and the order of evaluation was randomized (Figure 1).

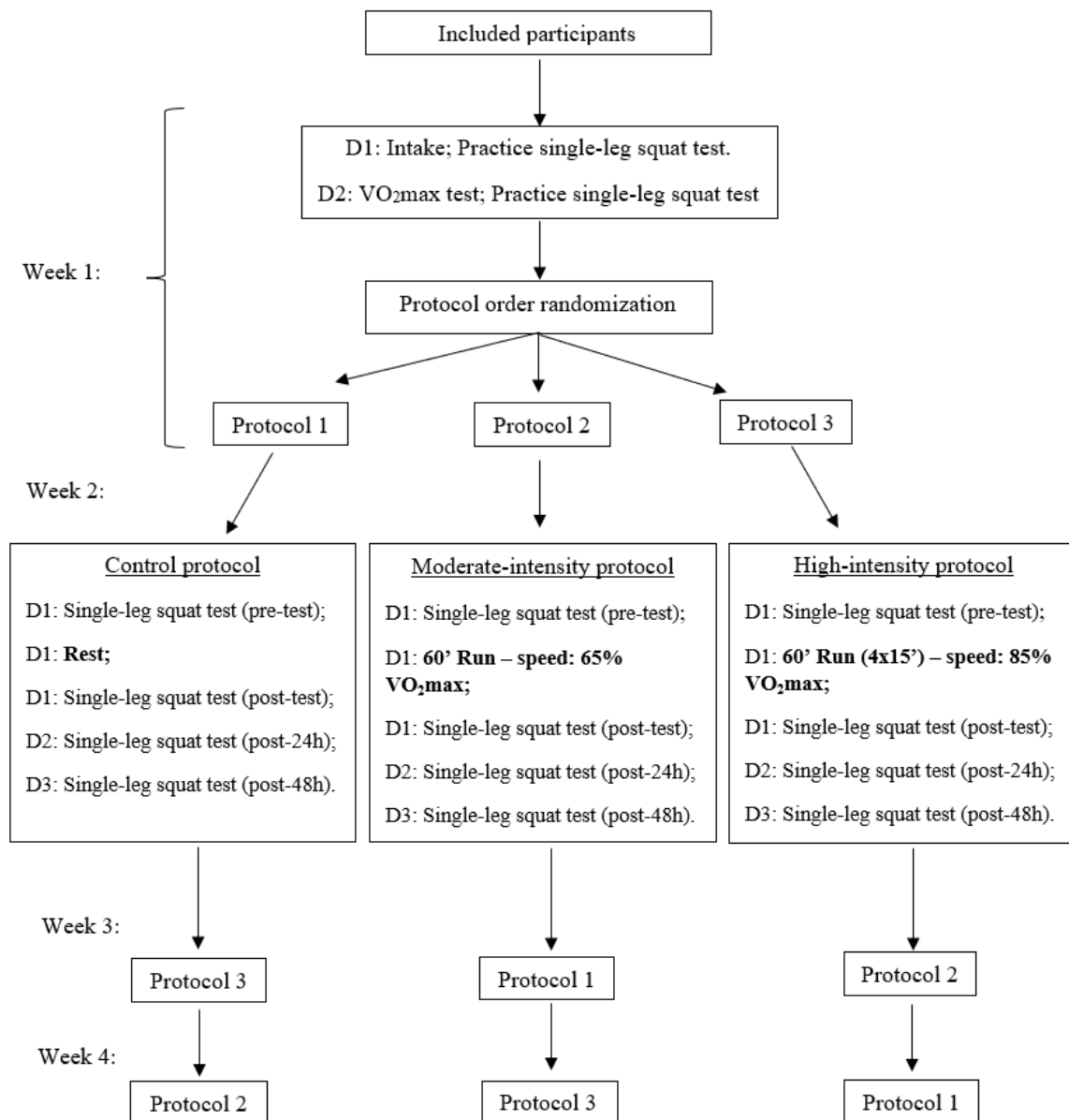


Figure 1. Experimental flowchart: Participants participated for four weeks. Two visits of testing were completed during the first week (Week 1): First visit (D1), intake information was collected, and participants practiced the single-leg squat test; Second visit (D2) consisted of VO₂max test and another practice of the single-leg squat test. All participants performed all protocols (running in moderate and high-intensity and control protocols) in randomized order. VO₂max: Maximum volume of oxygen consumed; D1, D2, D3: First, second, and third day of assessment, respectively.

Single-leg squat test

The single-leg squat test was adapted from Cardoso et al. (2021). Participants were instructed to stand barefoot on their dominant leg (i.e., the preferred leg to kick a ball) with their hands crossed behind their heads and foot perpendicularly aligned to a screen in front of them. The screen had two horizontal lines (upper and lower targets) separated vertically by 30 cm. The horizontal distance between the participant and the screen was adjusted to ensure

a minimum knee flexion peak angle of 40° to complete each squat repetition (Bittencourt et al., 2012; Petushek et al., 2021; Rees et al., 2019; Ugalde et al., 2015). A laser pointer was attached to a rigid cluster positioned above the knee parallel to the ground and aligned with the greater trochanter. The screen's vertical position was adjusted so the laser was centered on the lower target with the knee extended.

The single-leg squat test consisted of 60 seconds of uninterrupted squats by flexing and extending the lower limb and keeping the trunk upright and the contralateral foot off the ground. The participants were instructed to continuously move the laser from the lower (knee extended) to the upper targets (knee flexed) at their preferred speed. They could only reverse the direction of movement after the laser contacted or exceeded the target. A 30-second single-leg squat trial was completed before each pre-test to allow the participants to practice and warm up. The test was interrupted if the participant moved their hands or stance foot out of position or touched the support leg or ground with the non-dominant leg. The rate of perceived exertion (RPE) was assessed before and after each test. If a new trial was needed for pre-test, post-24h, post-48h, and control tests, participants rested for five minutes or until they returned to their initial RPE. No rest period was provided after the running protocols (i.e., post-test) were interrupted once the participants were expected to be fatigued from the running protocols.

A three-dimensional motion capture system (10 cameras, Oqus 7, Qualisys, Gothenburg, Sweden) was used to record kinematics during the single-leg squat test at a sample rate of 120 Hz. Before each single-leg squat test, three static trials were conducted in the orthostatic position. Only the dominant leg was evaluated using 33 retroreflective markers placed on the foot, shank, thigh, pelvis, and trunk.

VO₂max

To characterize the participants' aerobic fitness and normalize the intensity of the running protocols, VO₂max was directly estimated using a metabolic cart (HandyMET Clinic, MDI, Brazil). The VO₂max test was performed using an incremental treadmill protocol, with a fixed grade of 1% (Lourenço et al., 2011). The participants did not engage in any exercise before the test. After familiarization with the treadmill and equipment, a 3-minute warm-up at 8 km/h was performed before starting the test at an initial 9 km/h speed. The speed was increased by 0.5 km/h every 30 seconds until exhaustion, followed by a 5-minute recovery protocol - initial speed decreased by 60% of the maximum speed reached and reduced by 5% each minute (Lourenço et al., 2011). The heart rate (HR) and RPE were assessed every minute during the test and recovery. The VO₂ max was defined as the

maximum VO_2 observed during testing. The $\text{VO}_{2\text{max}}$ test was considered valid if two or more criteria were met at the end: (1) RPE > 9; (2) HR > 90% of 220-age; (3) respiratory exchange ratio > 1.1; (4) $\text{VO}_{2\text{max}}$ plateau; and (5) the person could not continue the test (Cortes et al., 2014; Quammen et al., 2012). All participants assessed had a valid $\text{VO}_{2\text{max}}$. The speed corresponding to that of $\text{VO}_{2\text{max}}$ was used to normalize the intensity of the running protocol (Billat, 2001; Encarnación-Martínez et al., 2020; Kaufman et al., 2006). The maximum HR during the test was used to verify the maintenance of the intensity during the running protocols (Garber et al., 2011; Kaufman et al., 2006; Pollock et al., 1998).

Protocols

The study consisted of three protocols: running in moderate and high intensities and control conditions. The running protocols were performed on a treadmill without inclination, and no exercise was conducted in the control protocol. HR and RPE were assessed every 5 min to ensure the protocol intensity (Bellenger et al., 2019; Garber et al., 2011; Impellizzeri et al., 2004; Kaufman et al., 2006; Pollock et al., 1998). To minimize the impact of recent training, participants refrained from exercising every week for two days before each experiment. The single-leg squat test was performed before (pre-test) and immediately after (post-test), 24h (post-24h), and 48h (post-48h) after each running protocol. During the control protocol, the participants performed the two single-leg squat tests, corresponding to the pre- and post-test of the running protocols, but rested before each squat test.

Before the running protocols started, participants warmed up on the treadmill for five minutes at a self-selected speed. The moderate-intensity protocol consisted of running for 60 minutes consecutively at a speed corresponding to 65% $\text{VO}_{2\text{max}}$ (Bellenger et al., 2019; Pollock et al., 1998; Powers and Howley, 2017). During this protocol, the HR should remain between 65 and 85% of HR_{max} and the RPE between 6 and 8 (Bellenger et al., 2019; Pollock et al., 1998; Powers and Howley, 2017). In the high-intensity running protocol, the participants ran four bouts of 15 min at 85% $\text{VO}_{2\text{max}}$ speed, with a 5-minute interval between bouts to recover at the preferred speed (Bellenger et al., 2019; Billat, 2001; Encarnación-Martínez et al., 2020; García-Pérez et al., 2014; Kaufman et al., 2006; Pollock et al., 1998). Again, to guarantee the high intensity of the protocol, the HR and RPE should remain higher than 85% HR_{max} and 8, respectively (Garber et al., 2011; Kaufman et al., 2006; Pollock et al., 1998). All the runners randomly performed one protocol per week.

Data analysis

Kinematic data for each protocol during the pre-test, post-test, post-24h, and post-

48h single-leg squat test were analyzed using Visual 3D (C-Motion, Inc., Rockville, Maryland, USA) and MatLab (MathWorks Inc., USA). A biomechanical model was created from the average of three static trials to compute the rotation zeros and define the local coordinate system for each segment. Linear displacements of the markers were filtered using a low-pass fourth-order Butterworth filter with a cutoff point of 6 Hz (Winter, 2009). The following lower limb joint angles in the sagittal plane were calculated: (1) ankle, angle between the foot and shank; (2) knee, angle between the shank and thigh; and (3) hip, angle between the thigh and pelvis (Portinaro et al., 2014). The Cardan sequence used was mediolateral, anteroposterior, and longitudinal.

Joint angles (cycle-normalized)

After calculating the joint angles, squat events were defined based on the knee flexion and extension peaks. Specifically, two consecutive knee extension peaks determined a single-leg squat cycle and a half-cycle corresponded to a knee flexion peak. During each squat cycle, the ankle, knee, and hip angles in the sagittal plane were normalized to 101 points, where points 0, 50, and 101 corresponded to the cycle's beginning, half, and end, respectively. The normalized curves for each cycle during the 60-second trials were averaged and extracted using Visual 3D. The mean curves from the ankle, knee, and hip angles during the single-leg squat for the moderate- and high-intensity running protocols and the control protocol were compared between assessment periods (pre-test, post-test, post-24h and post-48h).

Joint coordination (cycle-normalized)

Coordination was calculated with a continuous relative phase (CRP) measure (Hamill et al., 1999; Lamb and Stöckl, 2014). The CRP quantifies the phase relationship between two body segments, generating a new signal representing the difference in the phase angles of the two original signals (Lamb and Stöckl, 2014). We used a more robust approach to determine the CRP based on the Hilbert transform (Lamb and Stöckl, 2014), which is less sensitive to noise and non-sinusoidal data, features commonly observed in joint angles measures (Hamill et al., 1999; Van Emmerik et al., 2004).

The relative phase generated by the Hilbert transform is calculated based on the measured signal $x(t)$ and its Hilbert transform $H(t) = H(x(t))$ (Lamb and Stöckl, 2014). This procedure allows the transformation of any real signal into a complex analytical signal, where the Hilbert transform $H(t)$ of $x(t)$ is the imaginary part of the analytical signal (Feldman, 2011; Lamb and Stöckl, 2014). First, the amplitude of the data must be centered around zero

(Eq.1) before calculating the analytical signal using the Hilbert transform based on $x_{centered}(t_i)$.

$$x_{centered}(t_i) = x(t_i) - \min(x(t)) - (\max(x(t)) - \min(x(t))) / 2 \quad (\text{Eq. 1})$$

Then, the phase angle at time $t(i)$ can be calculated for each signal (Eq. 2), and the CRP between the two signals is computed by subtracting the phase angles from each other (Eq.3)

$$\phi(t_i) = \arctan(H(t_i) / x(t_i)). \quad (\text{Eq. 2})$$

$$\text{CRP}(t_i) = \phi_1(t_i) - \phi_2(t_i) \quad (\text{Eq. 3})$$

The result was a new time series with values ranging from 0° to 180° (in-phase and anti-phase, respectively). When the two segments are in-phase, both are coordinated, moving in the same direction, whereas in anti-phase coordination, the segments move in opposite directions.

The normalized curves from the ankle, knee, and hip in the sagittal plane were extracted from Visual 3D to calculate the joint coordination. Each normalized cycle for each joint during the 60-second trial was used to calculate the CRP based on the Hilbert transform between the ankle-knee and knee-hip in the sagittal plane. The CRP curves of ankle-knee and knee-hip coupling angles from each cycle were averaged, and mean curves were compared between assessment periods for all protocols.

Regularity of joint and coordination

The regularity of the joint and coordination (i.e., CRP of ankle-knee and knee-hip coupling angles) was calculated using Multiscale Entropy (MSE). MSE estimates the degree of randomness of a time series at multiple time scales (τ) using a coarse-graining procedure (Costa et al., 2002). At each time scale, entropy was determined using the Sample Entropy (SampEn) method. For scale one, MSE calculates the SampEn of the original time series. The coarse-graining procedure divides the original time-series into non-overlapping windows by successively averaging consecutive data points into a new coarse-grained time-series and calculating the SampEn for each time series (Costa et al., 2002).

SampEn is the negative natural logarithm of the conditional probability that two sequences of m data points close within a tolerance r remain close when the sequences are increased to $m + 1$ data points (Richman and Moorman, 2000). To select *the* m (template length) and r (radius of similarity) hyperparameter values, we adapted the criteria suggested

by Ramdani et al. (2009). We computed the median value of SampEn and the standard error of the SampEn estimates across all joint and coordination time series, with $.05 < r < 1$ in steps of .05 and $m = 2, 3, 4, 5$ (Supplementary material 1). Additionally, to assess the convergence point and maximize the precision of the SampEn estimates, we computed the variance of SampEn for different m values relative to the mean and calculated the percentage of the standard error relative to the SampEn estimates at each value of r . We selected and fixed the hyperparameters across all scales at $m = 2$ and $r = .20$. The length of the coarse-grained time series was the quotient between the length of the original time series (≈ 7200 points) and the number of scales ($\tau = 35$), where the shortest time series had at least 200 points (14^m with $m = 2$) (Gow et al., 2015). Filtering the raw time series was necessary for MSE analysis because general trends and low-frequency drifts can overestimate the entropy values (Gow et al., 2015). The lower frequency (f_L) that should be included in the MSE analysis was determined based on the length of the time-series in seconds (t), the number of points in the last scale (N_{Tm}), and the hyperparameter m (Eq. 4) (Gow et al., 2015). Thus, the ankle, knee, and hip time-series were filtered with a high-pass filter with a cutoff point of 0.5 Hz before calculating the regularity. The filtered joint time-series was used to calculate the CRP of the ankle-knee and knee-hip in the sagittal plane before computing the entropy. MSE analysis was then used to calculate the regularity of the filtered joint motions and coordination patterns.

$$f_L = N_{Tm} / 2 \times (m + 1) \times t \quad (\text{Eq. 4})$$

The MSE outcome, the MSE index, was the area under the curve of SampEn over multiple scales. During the single-leg squat test, the MSE index of ankle, knee, and hip displacement, along with ankle-knee and knee-hip coordination were compared with between assessment periods for all three protocols. A higher MSE index (i.e., higher entropy) relates to more random dynamics or uncertainty about future behavior, and a lower entropy (i.e., lower MSE index) indicates more regular dynamics or more predictable behavior (Costa et al., 2002; Gow et al., 2015).

Statistical Analysis

A one-dimensional Statistical Parametric Mapping (SPM) one-way repeated measure analysis of variance (ANOVA) compared the mean normalized joint displacement and coordination through time (pre-, post, post-24h, and post-48h-test) during single leg squat test at each running intensity protocol (moderate and high-intensity and control) (Pataky, 2012). SPM has been suggested to be a superior method for analyzing normalized time series

because the analysis of the entire temporal domain prevents regional focus bias and is more representative of the movement dynamics than just one point in time (i.e., joint peaks) (Pataky et al., 2013).

The effects of running at different intensities and control protocols on the regularity of joint and relative phase were analyzed using a two-way repeated measures ANOVA with Protocol (moderate and high-intensity run, and control) as a between-subjects factor, Time (pre-test, post-test, post-24, and post-48) as a within-subjects factor. Post-hoc comparisons were made using Bonferroni correction. Partial eta squared (η^2_p) estimated the effect sizes for all ANOVA analyses and were interpreted as small (.01), medium (.06), or large ($\geq .14$) (Cohen, 1988). Statistical analyses were performed using SPSS Statistics version 21 (SPSS Inc. Chicago, IL, USA) with a significance level of 0.05.

Results

Thirty participants (20 men and 10 women; mean (SD) age:38.13 (± 9.95) years, height:1.70 (± 0.08) m, weight:69.64 (± 10.17) kg completed the study. The runners had an average running experience of 6.05 (8.7) years, ran 42.65 (± 24.46) km/week with a pace of 05:15 ($\pm 00:45$) min/km, and had a cardiorespiratory fitness (VO_{2max}) of 48.26 (± 6.05) ml.min⁻¹.kg⁻¹. Fifteen participants reported extra activities besides running (e.g., strength training, cycling), and only five reported a previous injury in the past six months. The mean knee flexion peak during the single-leg squat tests was 48.45°.

Joint angles

The normalized joint angle curves during the single-leg squat tests and the results of SPM analyses at each protocol are shown in Figure 2. The SPM one-way ANOVA of the ankle, knee, and hip curves in the sagittal plane did not reveal an effect of Time (pre-, post-, post-24h-, and post-48h-test) during the entire cycle. The SPM inference plots are shown in Supplementary Figure 2. Additionally, the movement amplitude during the squat cycles was similar between protocols for all three joints. Specifically, the mean and range amplitudes during moderate and high-intensity run and control protocols were 16.66° (16.03° to 17.27°) at the ankle, 39.92° (39.37° to 40.68°) at the knee, and 24.43° (23.46° to 25.65°) at the hip joint.

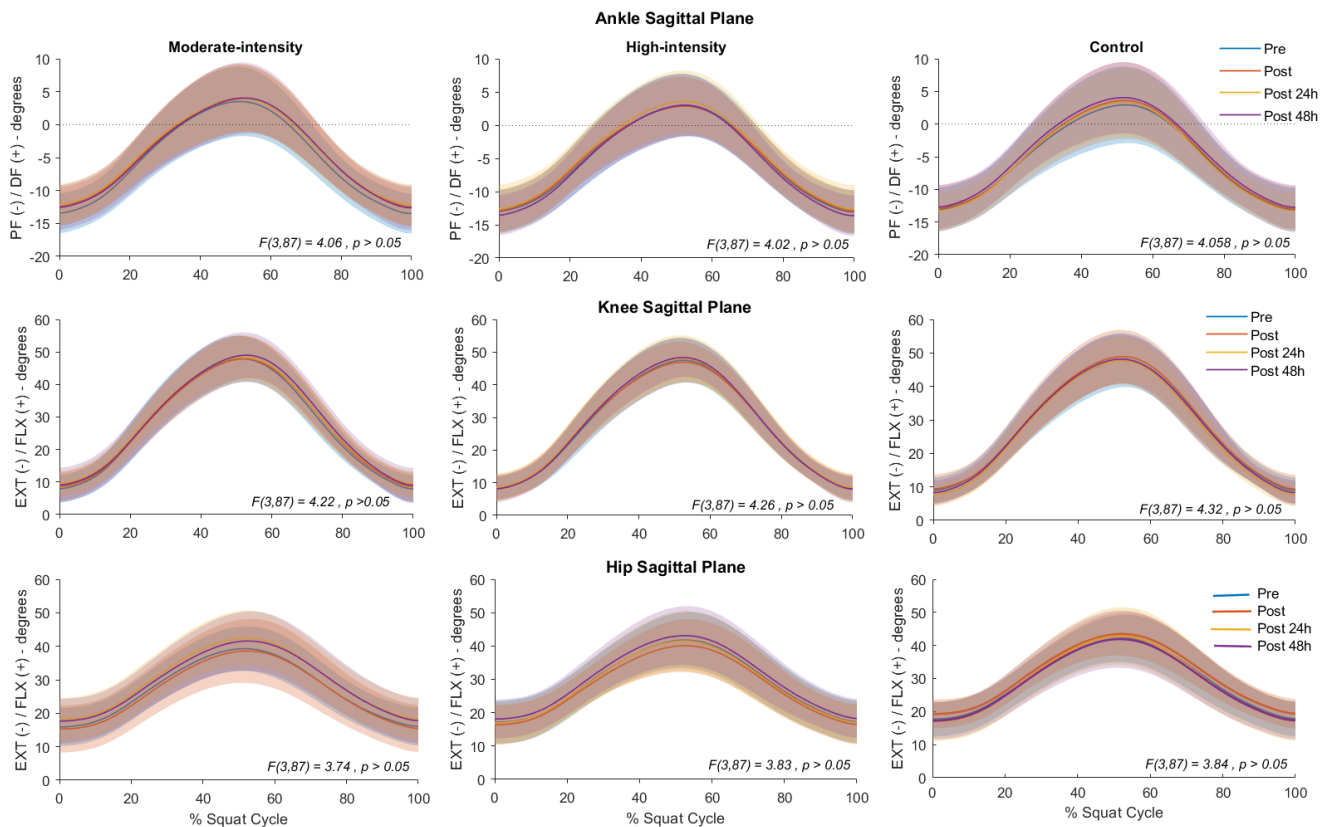


Figure 2. Joint angles: Average of joint angles curves (y-axis) in relation to the percentage of the single-leg squat cycle (x-axis) and the results of the Statistical parametric mapping (SPM) one-way repeated measures ANOVA analyses between Times (pre-test, post-test, post-24h, and post-48h) at each protocol (moderate- and high-intensity run and control). No differences were observed between times for all joint angles. Left column: moderate-intensity protocol; Middle column: high-intensity protocol; Right column: control protocol; First row: ankle angles; Middle row: knee angles; Third row: hip angles; Blue lines: pre-single-leg squat test; Orange lines: post-test; Yellow line: post-24h test; Purple lines: post-48h test. DF: dorsiflexion; PF: plantar flexion; FLX: flexion; EXT: extension.

Joint coordination

The normalized relative phase angle curves and the results of SPM analyses during the single-leg squat tests at each protocol are shown in Figure 3. No Time effect (pre-, post-, post-24h-, and post-48h-test) was observed on ankle-knee and knee-hip relative phase mean angles during the single-leg squat test in none of the protocols (Supplementary Figure 3). In general, both the joint coordination patterns were in phase throughout the squat cycle. For example, the mean ankle-knee coordination values were 1.81° , 1.89° , and 1.67° for the moderate, high, and control protocols. Similarly, knee-hip coordination was in phase in the moderate (mean: 3.21°), high-intensity (3.28°), and control (2.75°) protocols. In conclusion, the cycle-normalized outcomes did not detect an effect of running at different intensities on the movement patterns of recreational runners.

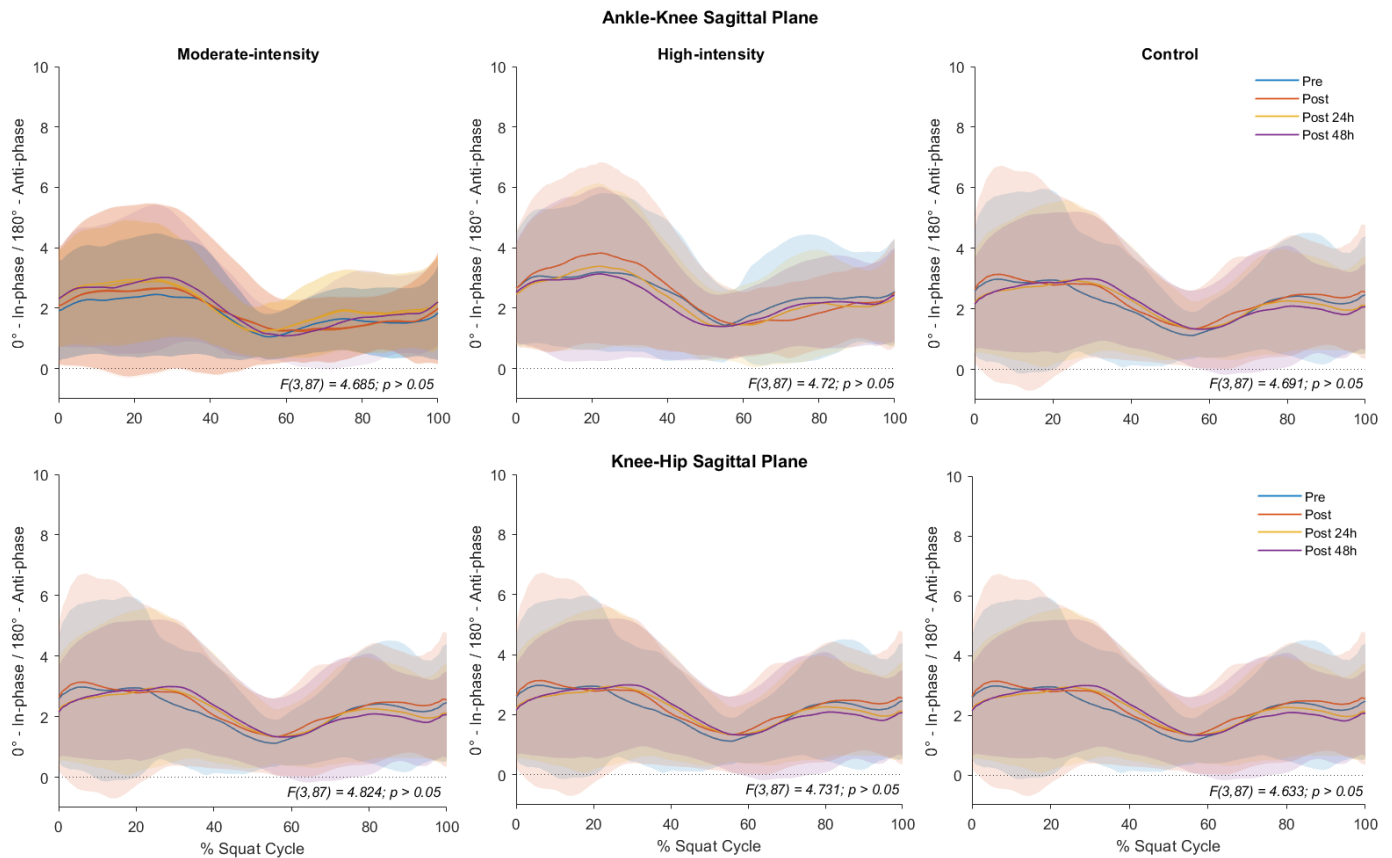


Figure 3. Coordination: Relative-phase angles curves (y-axis) in relation to the percentage of the single-leg squat cycle (x-axis) and the results of the Statistical parametric mapping (SPM) one-way repeated measures ANOVA analyses between Times (pre-test, post-test, post-24h, and post-48h) at each protocol (moderate- and high-intensity run and control). No differences were observed between times for both coordination patterns. Left column: moderate-intensity protocol; Middle column: high-intensity protocol; Right column: control protocol; First row: ankle-knee relative phase angles; Last row: knee-hip relative phase angles; Blue lines: pre-single-leg squat test; Orange lines: post-test; Yellow line: post-24h test; Purple lines: post-48h test; 0°: in-phase coordination; 180°: anti-phase coordination.

Regularity of joint and coordination patterns

MSE analysis computed the regularity of the joint angles and coordination during the single-leg squat tests (Figures 4 and 5). The MSE index compared pre-, post-, post-24h, and post-48h tests between different protocols. The two-way mixed ANOVA revealed a Time effect in the ankle and knee entropy, and the post-hoc revealed a decreased MSE index after 48h independently of the protocol (Table 1). No other effects were observed in joint regularity.

There were significant Time and Time $\times$ Protocol interaction effects only in the ankle-knee coordination entropy (Table 1), and the post-hoc comparisons showed lower entropy values on the post-test following the moderate and high-intensity run. This result indicated no difference on the pre-test between intensities, an increased regularity immediately after both running protocols, no prolonged effect differences on post-24h and post-48h tests, and no differences in the control protocol (Figure 7).

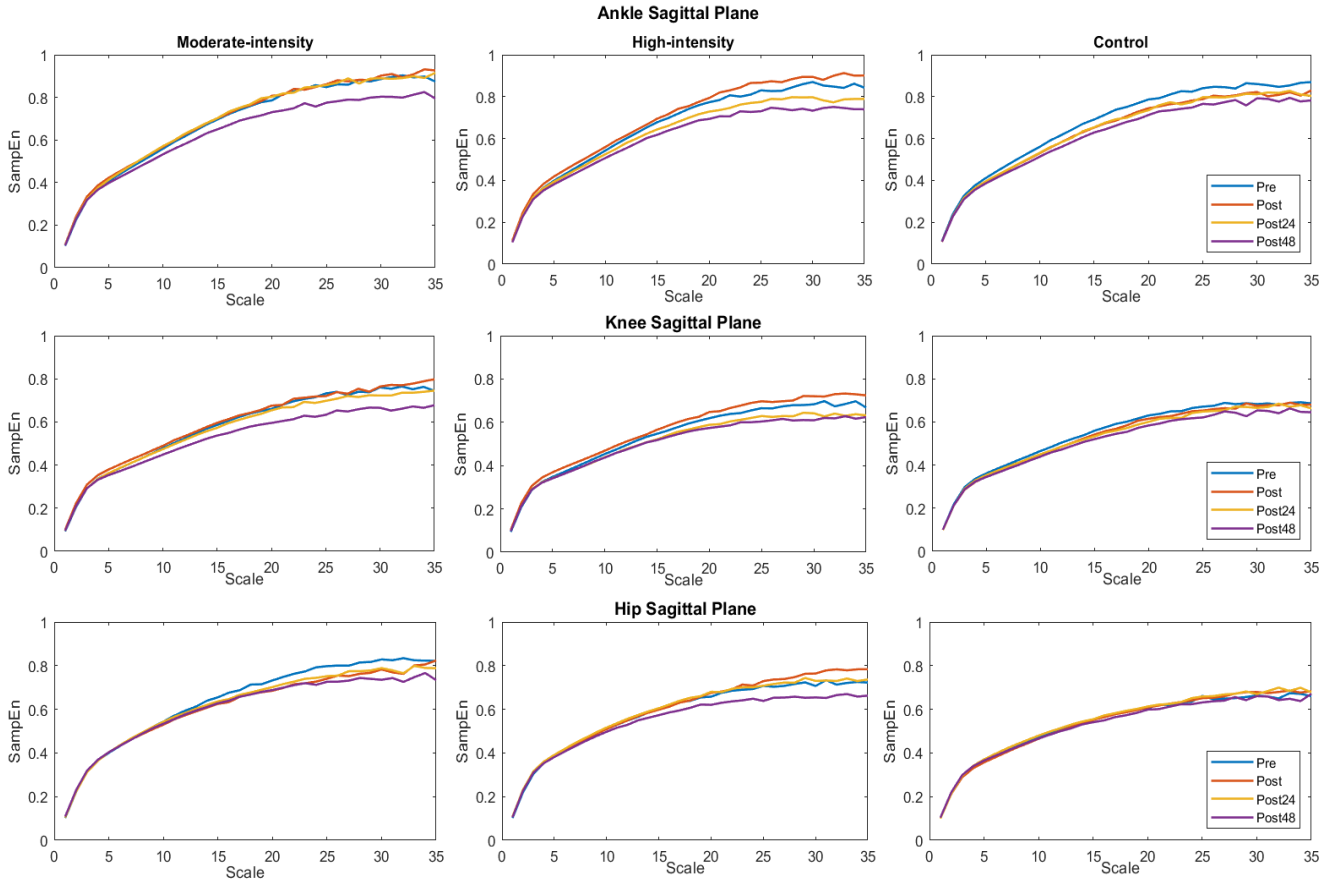


Figure 4: Multiscale entropy Index (MSE Index) of the ankle, knee, and hip joints in the sagittal plane during the single-leg squat test before and after moderate, high-intensity, and control protocols. Blue lines: pre-test; Orange lines: post-test; Yellow lines: post-24h; Purple lines: post-48h.

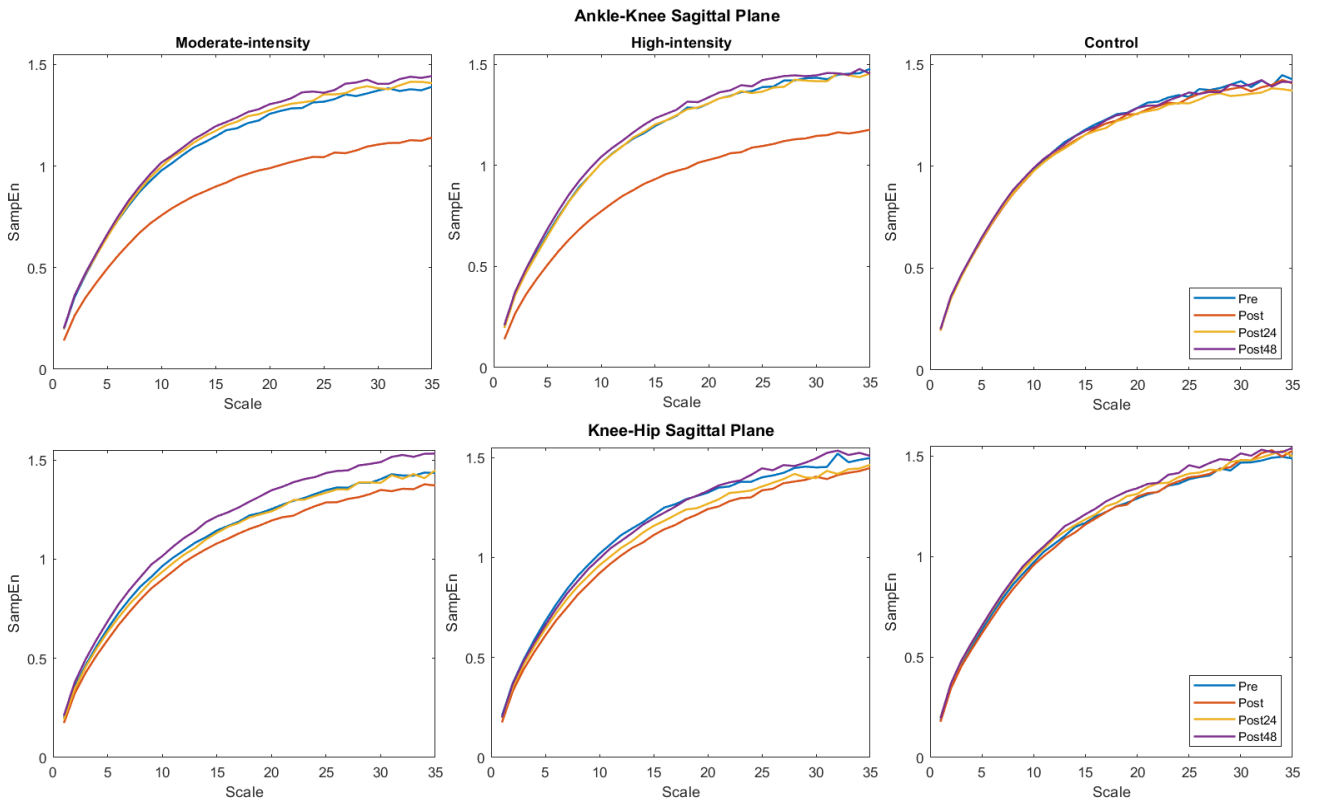


Figure 5: Multiscale entropy of coordination between the ankle and knee and the knee and hip in the sagittal plane during the single-leg squat test before and after the moderate, high-intensity, and control protocols. Blue lines: pre-test; Orange lines: post-test; Yellow lines: post-24h; Purple lines: post-48h.

Table 1: Two-way mixed-model ANOVAs with Time and Protocol as fixed factors and participants as a random factor of the analyzed Multiscale Entropy (MSE) outcomes. Means and standard deviations are reported for the pre- and post-tests for the moderate, high-intensity, and control protocols. The results of the two-way mixed-model ANOVAs are also reported, including F -values, p -values, and partial eta squared (η^2_p).

MSE index	Time	Protocol			Statistical effect								
		Moderate	High	Control	Time			Protocol			Time x Protocol		
		Mean (SD)	Mean (SD)	Mean (SD)	$F_{3,87}$	p	η^2_p	$F_{3,87}$	p	η^2_p	$F_{3,87}$	p	η^2_p
Ankle (bits ²)	Pre	24.39 (8.95)	23.58 (8.67)	23.98 (9.19)	9.63	<.001*	.10	.251	.778	.00	1.39	.22	.03
	Post	24.45 (7.24)	24.31 (7.62)	22.61 (8.11)									
	24h	24.54 (9.33)	22.21 (7.34)	22.57 (8.25)									
	48h	22.5 (8.31)	21.2 (6.57)	21.7 (7.41)									
Knee (bits ²)	Pre	20.71 (7.5)	19.17 (5.5)	19.45 (6.06)	9.74	<.001*	.10	.619	.541	.01	.91	.488	.02
	Post	20.83 (5.72)	19.8 (5.01)	18.9 (5.62)									
	24h	20.15 (6.32)	18.1 (5.36)	18.66 (5.54)									
	48h	18.7 (6.07)	17.8 (4.94)	18.1 (5.45)									
Hip (bits ²)	Pre	22.86 (7.26)	20.62 (5.98)	19.0 (5.55)	1.92	.127	.02	2.53	.086	.05	.539	.778	.01
	Post	21.5 (5.03)	20.93 (5.16)	18.93 (5.26)									
	24h	21.7 (6.42)	20.64 (6.9)	19.04 (5.03)									
	48h	21.35 (7.03)	19.35 (5.76)	18.39 (4.94)									
Ankle-Knee (bits ²)	Pre	37.64 (8.72)	39.4 (8.13)	38.9 (9.37)	12.03	<.001*	.12	.560	.573	.01	2.99	.008*	.06
	Post	31.0 (10.2)	32.1 (8.5)	38.3 (9.37)									
	24h	39.3 (7.05)	40.2 (7.79)	37.7 (9.68)									
	48h	39.3 (8.2)	40.5 (8.65)	38.65 (8.13)									
Knee-Hip (bits ²)	Pre	38.1 (8.16)	40.1 (8.97)	39.3 (7.88)	2.02	.115	.02	.502	.607	.01	.292	.940	.00
	Post	36.7 (9.98)	38.1 (8.39)	38.95 (7.13)									
	24h	37.96 (9.98)	38.7 (7.16)	39.88 (6.44)									
	48h	40.58 (7.33)	40.16 (8.39)	40.56 (6.07)									

SD: standard deviation; *: statistical significance ($p < 0.05$); Post-hoc pairwise comparisons with Bonferroni adjustment are shown in Figure 6.

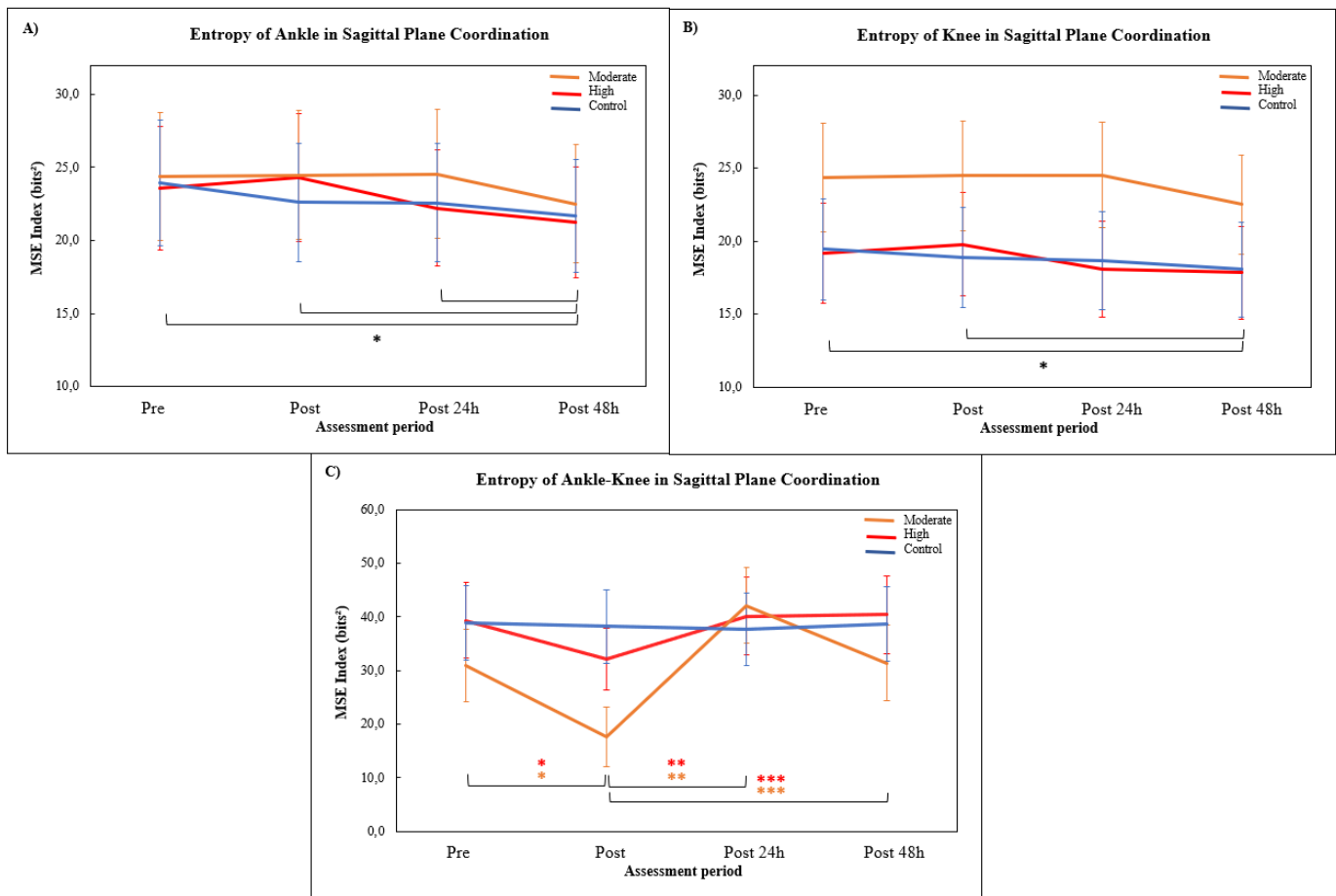


Figure 6: Multiscale entropy (MSE) index (y-axis) relative to assessment periods (x-axis) and results of post-hoc comparisons with Bonferroni adjustments from the two-way mixed ANOVA between Protocol and Time. **A)** Ankle entropy is lower at Post48h (*) compared to Pre- ($p < .001$), Post- ($p < .001$), and Post24h-test ($p = .012$) ($F_{3,85} = 7.9$; $\eta^2_p = .22$). **B)** Knee entropy is lower at Post48h (*) compared to Pre- ($p = .001$) and Post-test ($p < .001$) ($F_{3,85} = 8.97$; $\eta^2_p = .24$). **C)** Ankle-Knee entropy is lower on Post-test compared to Pre- (*), Post24h- (**), and Post48h-test (***) during moderate-intensity (*: $p = .003$, **: $p < .001$, ***: $p = .001$; $F_{3,85} = 7.71$; $\eta^2_p = .21$), and high-intensity protocols (*: $p = .001$, **: $p < .001$, ***: $p = .001$; $F_{3,85} = 7.98$; $\eta^2_p = .22$). Multiscale Entropy Index (MSE Index). *, **, ***: statistical significance ($p < 0.05$). Blue lines: Control; Orange lines: Moderate-intensity protocol; Red lines: High-intensity protocol.

Discussion

The present study investigated the immediate and prolonged effects of moderate- and high-intensity running protocols on lower-limb joint angles, coordination, and regularity during a 60-second single-leg squat test in recreational runners. As hypothesized, cycle-normalized joint angles and coordination did not differ after the running protocols. Similarly, as predicted, the regularity of the joint coordination increased immediately after both running protocols and did not change after the control protocol. However, no differences during the immediate post-test were observed as a function of fatigue protocol in single joint regularity. Contrary to expectations, there was no difference between moderate- and high-intensity running protocols in joint and coordination regularity. Similarly, no differences were observed after 24h or 48h on coordination regularity, but lower entropy (increased regularity) values were shown post-48h in joint regularity, independently of the protocol. Additionally,

there were no differences in the joint and relative phase normalized angles or regularity before any of the protocols or after the control protocol. This study demonstrated that joint coordination entropy was sensitive in detecting the immediate effects of running.

Differences in coordination patterns were observed during the single-leg squat test immediately after the running protocols. Compared to the pre-test, an entropy reduction of 17.64% after moderate-intensity and 18.56% following high-intensity running protocols were observed only at ankle-knee coordination in the sagittal plane. The single-leg squat coordinative pattern alterations can be interpreted as a compensatory strategy to accomplish the task (Ksoll et al., 2022). Different running intensities induced recreational runners to adopt a more regular and predicted coordination between the ankle and knee to accomplish the task. Additionally, both running protocols had a large effect ($\eta^2_p = .21$ and $.22$ for moderate and high-intensity, respectively) on ankle-knee coordination regularity. At the same time, no differences were observed in the MSE index pre-test values of running protocols or across time assessment for the control protocol. These results indicate that both running protocols might have decreased the capacity of the runners to deal with the task demands (Dierks et al., 2010; Kellmann et al., 2018; Monjo et al., 2015). Therefore, evaluating the regularity of ankle-knee coordination during the single-leg test can be useful to track the response from training and fatigue even without maximal effort, possibly helping to establish strategies to prevent injuries due to overtraining.

In contrast, the knee-hip coordination regularity did not change after running at different intensities. During the task, participants were required to continuously perform single-leg squats for 60 seconds without moving the stance foot out of position or touching the leg or ground with the non-stance leg. The participants had to overcome a performance and a balance component to complete the task. Accordingly, the task demand strongly constrained the coordination between the ankle and knee (i.e., fixed foot). In contrast, since the trunk was free to adjust during task execution, the knee-hip coordination was less constrained (i.e., the hip could move in different directions). Thus, because of the single-leg squat requirements, the interaction between hip and knee had more freedom to adapt to the decreased capacity of the individuals after running and still accomplish the task. Similarly, studies have shown that the entropy of hip and knee coordination was not affected by fatigue during single-leg tasks in healthy participants and elite athletes (Hollman et al., 2020; Stock et al., 2016). This behavior indicates that the movement and coordination pattern adopted by the participants after running protocols seemed to be dependent on the task's constraints (McGregor et al., 2009; Newell, 1986). Therefore, adopting a more regular coordination pattern in the most constrained joint coupling may be a strategy for dealing with the reduced

capacity during task execution.

No differences were observed in joint regularity immediately after the running protocols. The ankle, knee, and hip MSE index were similar at pre-tests and did not alter on post-test for all protocols. Previous studies investigating the influence of exercise and fatigue on joint entropy reported contradictory results (Bauer et al., 2017; Carvalho et al., 2023; Schütte et al., 2018, 2015). These differences may be related to (1) population, tasks, protocols, and data analysis, or (2) entropy measures that only analyzed the regularity at one time scale. The first could be minimized by analyzing and reporting the percent change within individuals rather than just the absolute values. However, it is still possible that different task demands may impose different adaptive responses to stressful activities. The latter point indicates that traditional approaches used by these studies to measure regularity (e.g., SampEn and Control Entropy) could have failed to account for the multiple time scales inherent to biological signals and led to erroneous characterization of the signals (Costa et al., 2005). It has been argued that non-complex, uncorrelated signals (i.e., white noise), when compared to complex, correlated signals (i.e., biological signals), return higher entropy values on the first scale that do not correspond to the structural nature of the signal at multiple scales (i.e., higher entropy of biological signal) (Costa et al., 2005). We calculated the entropy with a more robust method and analyzed the MSE curve profile over 35 scales. In this study, the joint regularity observed on the first scale (i.e., the scale used in a traditional SampEn analysis) differed from the higher scales, as shown by the current MSE analysis (Figure 5). For example, the ANOVA revealed significantly lower entropy (MSE index) at 48h compared to pre- and post-test on ankle and knee joints. In contrast, we ran an additional analysis and did not observe differences between times with the traditional single scale SampEn method ($p > 0.05$), and a tendency for lower ankle and knee SampEn values (not significant) was observed at the pre-test on all conditions. Thus, studies reporting joint regularity analyzed by only one entropy scale should be interpreted cautiously. In addition, our results suggested that joint regularity may not be sensitive enough to capture the immediate effect of running. Once the individual parts can be organized differently to produce the same coordination patterns when performing the same task, the between-joints relationship can be more informative than the investigation of the joints themselves (Hamill et al., 2012). Therefore, coordination regularity seems to be a better outcome for investigating the immediate effect of running at different intensities on movement patterns than joint regularity.

Lower entropy was observed on the ankle and knee after 48h of protocols, compared to pre-, post-, and post-24-test (Table 1). No prolonged effects of running (post-24 or post-

48) were observed on the regularity of the hip or the ankle-knee and knee-hip relative phases. The one-way ANOVA revealed a Time effect on ankle and knee regularity, independently of the protocols (Table 1). Since the consequences of fatigue have been reported for up to 48 to 72 hours (Clermont et al., 2020; Martínez-Navarro et al., 2021; Thomas et al., 2018), the lower entropy observed after 48 hours in joint regularity can be related to an ongoing recovery process. Training routines and exercises can induce micro-injury and inflammatory responses in the muscle and connective tissues within 12h and reach their peak at 48h following the exercise, especially when the demand exceeds the ability of the muscle to resist the load applied (Cheung et al., 2003; Smith, 1991). The muscle damage and inflammatory response induced by exercise can alter the muscle temporal recruitment patterns, resulting in changes in muscle coordination and segment motion (Cheung et al., 2003; Smith, 1991). Therefore, exercise-induced muscle inflammation can be related to an ongoing recovery process of the musculoskeletal system at 48h following the running protocols, which could contribute to the more regular movement pattern observed at the ankle and knee joints. Still, more studies are needed to clarify our results since the time to recovery is an individual and multifactorial process (Kellmann et al., 2018). Thus, this study is a starting point to understand better the prolonged effect of different exercise intensities.

No differences between times (pre-, post-, post-24, or post-48) were observed on joint or relative phase angles normalized by the squat cycle (Figures 3 and 4). Specifically, the SPM one-way repeated measures ANOVA did not reveal a time effect of running or control protocols on ankle, knee, hip, ankle-knee, or knee-hip normalized mean angle curves (Supplementary materials 2 and 3). Similarly, Hollman et al. (2020) demonstrated that lower limb joint angles (i.e., mean and peak angles) during a single-leg task were insufficiently responsive to detect exercise-induced changes. Running-induced modifications in movement patterns can be subtle and undetectable by conventional analyses of average cycle-normalized data, as they do not consider changes between cycles (Hamill et al., 2012; Hollman et al., 2020; Preatoni et al., 2013). Between-cycle fluctuations provide more complete information about the movement strategies used to perform a task (Preatoni et al., 2013). For instance, despite the predominantly in-phase coordination pattern during the entire squat cycle, instants of anti-phase coordination patterns tend to occur during the single-leg squat during moments of imbalance when one joint stops or changes direction while the other moves further in the same direction (Ksoll et al., 2022). These changes in coordination patterns could indicate the strategy used in response to physical stress and are not captured by cycle-normalized approaches. Therefore, measures that do not consider the time-dependent characteristics of human movement may lead to misinterpretation of the training load.

This study evaluated only the joint angles and coordination patterns in the sagittal plane, which could be a study limitation. Lower limb injuries have been frequently related to ankle, knee, and hip movements in the frontal and transverse planes (Bittencourt et al., 2012; Chang et al., 2021; Resende et al., 2016). However, single-leg squat and running tasks occur predominantly in the sagittal plane. Additionally, the movement pattern in other planes may be too variable and individual, making it challenging to observe group differences between times and protocol. The single-leg task chosen to investigate the effect of running imposed specific constraints to the movement pattern that may not be applied when a different task is assessed. Distinct tasks impose different demands and coordination patterns that could be affected by the exercise (McGregor et al., 2009; Newell, 1986). However, we proposed a simple, fast, and reliable single-leg squat test that can serve as a screening tool for different activities in clinical and sports environments. The study had a small sample size, reducing statistical power and limiting the generalizability (Hackshaw, 2008). Based on the large effect sizes supporting our findings, we believe the approach adopted can improve the knowledge of the impact of training and fatigue on movement patterns.

Conclusion

Recreational runners demonstrated a more regular lower-limb coordination pattern immediately after moderate and high-intensity runs, but no prolonged effect was observed. Specifically, running decreased the entropy of ankle-knee coordination in the sagittal plane during the single-leg squat test, even without maximal effort. An increase in regularity was observed on ankle and knee joints after 48h, independently of the protocol. Moreover, no differences were observed on the pre-test for all variables or control protocol. We demonstrated that the analysis of cycle-normalized kinematic curves, either joint angles or coordination, was not sensitive enough to detect the effect of running on movement patterns. Additionally, it was observed that analyzing how the joints interact over time (coordination regularity) can be more sensitive to evaluate changes in the musculoskeletal system after exercise than assessing joint regularity. In conclusion, measuring the effect of running at different intensities on the regularity of coordination patterns during functional tests is valuable for identifying the athlete's responses to exercise. Future studies should continue to investigate exercise- and training-induced changes and the time to recovery on joint and coordination regularity and its possible relationship with injury occurrence.

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.

Funding

The authors acknowledge the financial support offered by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil (CAPES, Finance Code 001) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil (CNPq, Process: 423731/2021-1).

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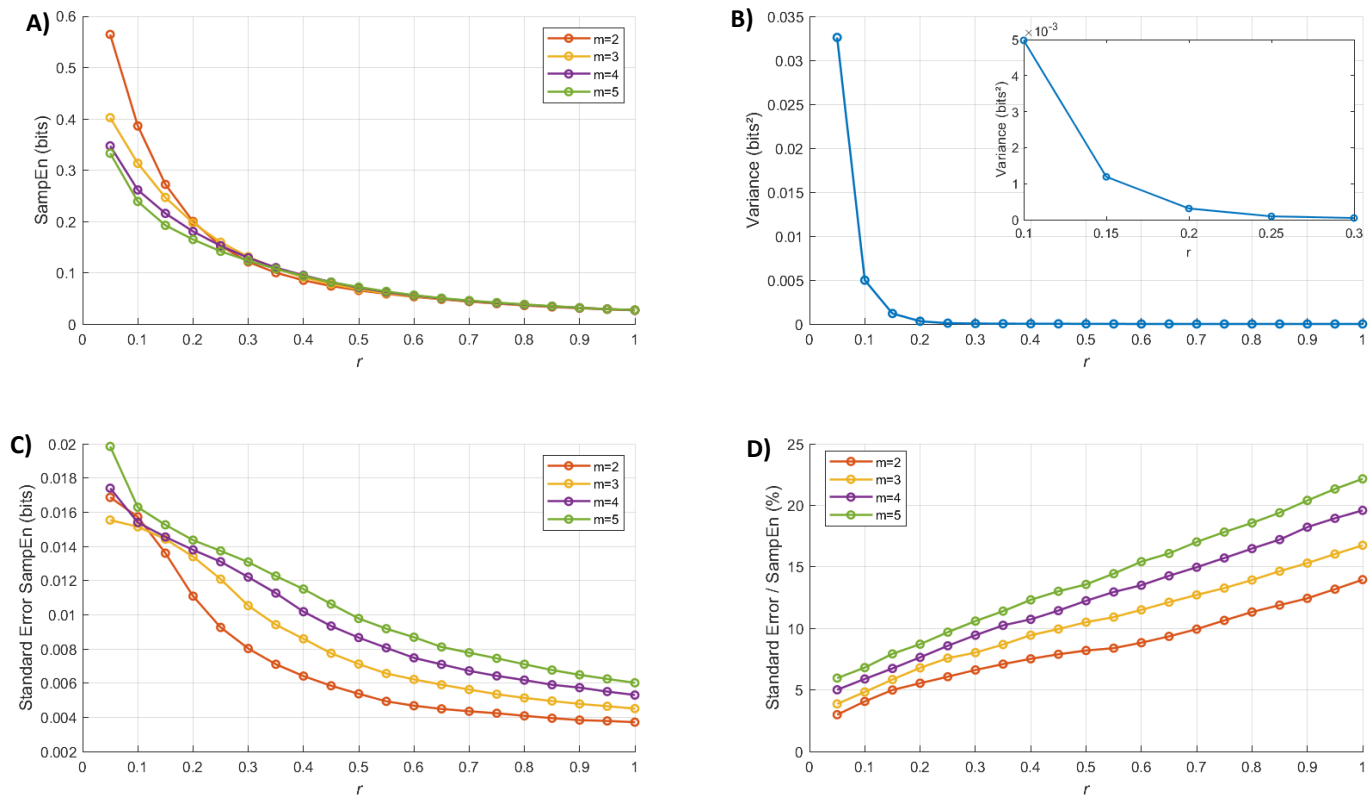
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Supplementary Materials

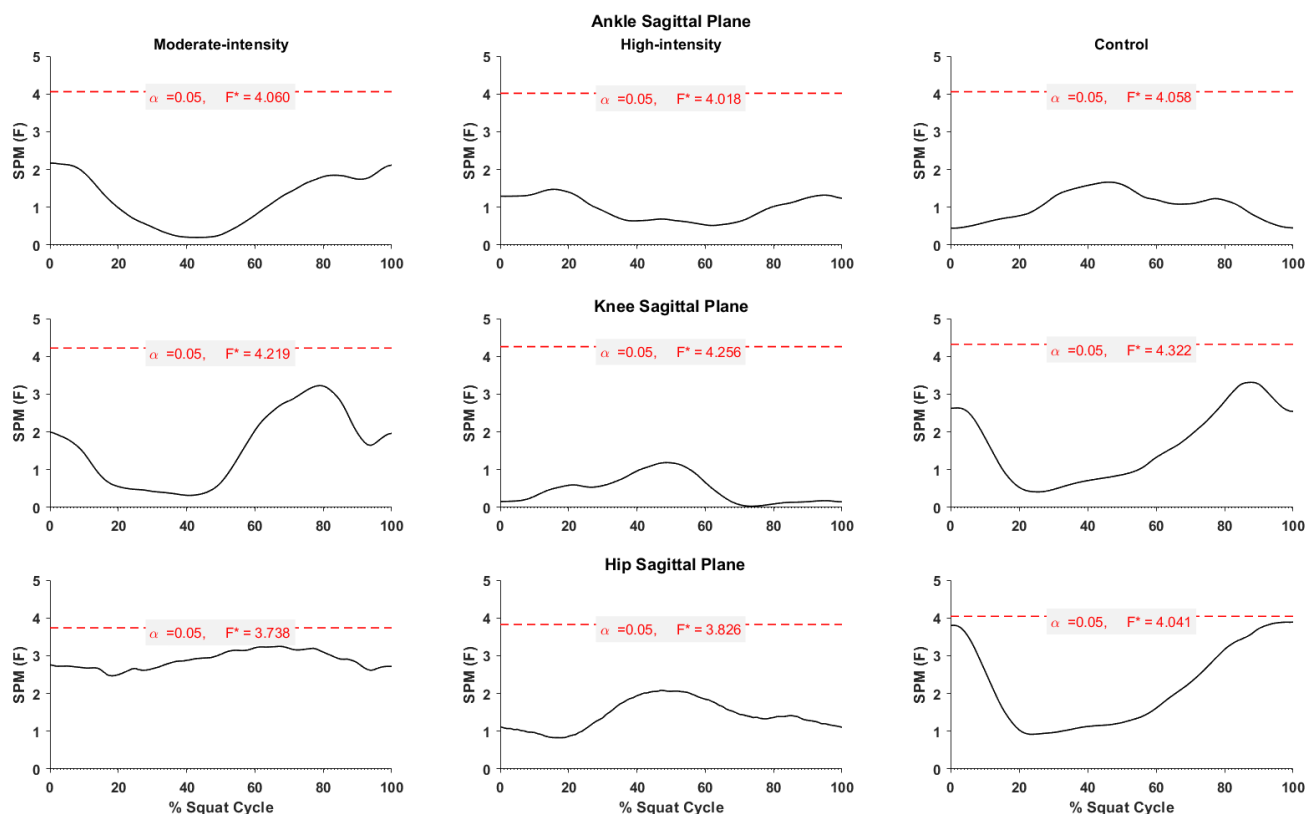
Supplementary Figure S1

Sample Entropy of Ankle-Knee Coordination Sagittal Plane - Moderate-intensity



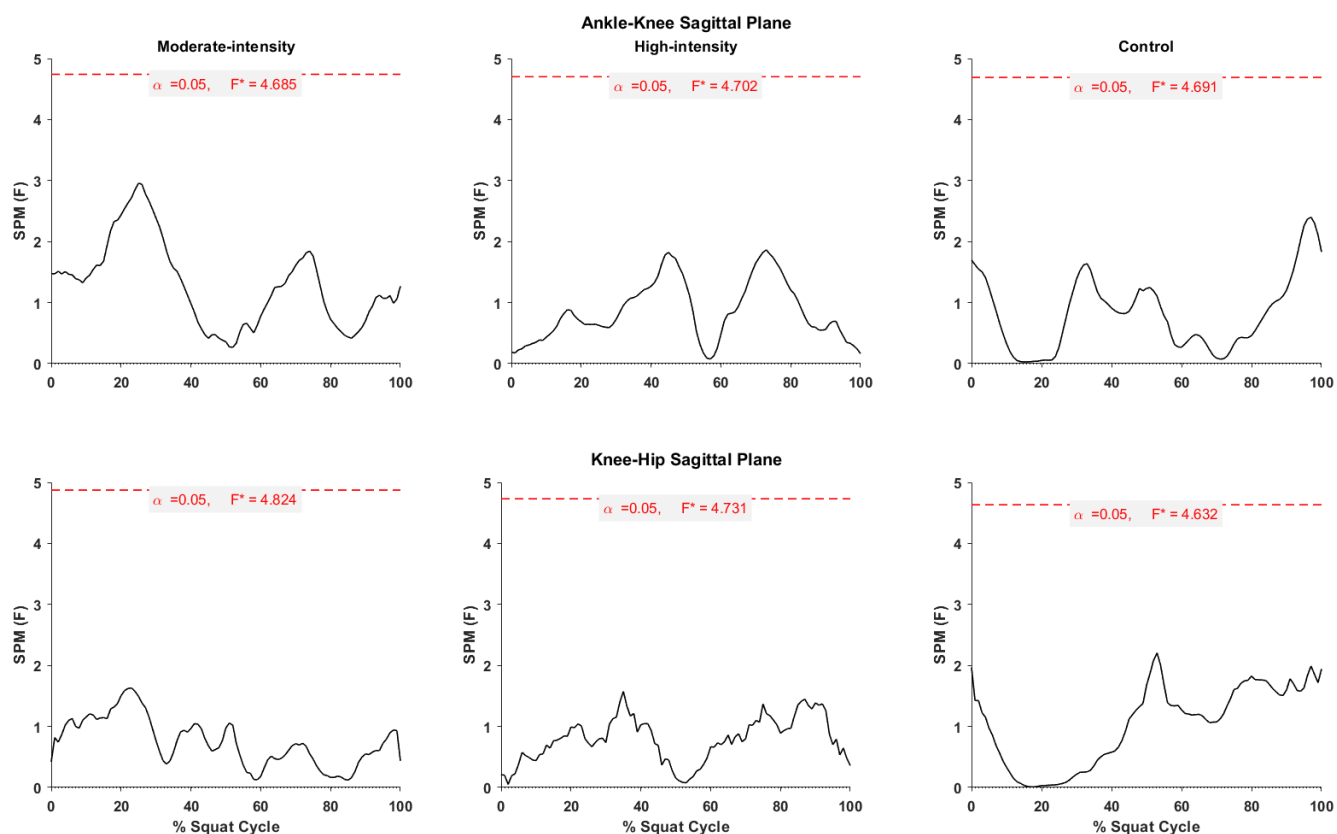
Supplementary Figure S1: Example of Sample Entropy (SampEn) hyperparameters selection, adapted from the criteria proposed by Ramdani et al. (2009). Ankle-Knee relative phase angle in sagittal plane at single-leg squat test from four assessment periods (pre-, post-, post24h-, and post48h-tests) during moderate-intensity running protocol were analyzed using $\text{SampEn}(m, r, N)$. We examined m from 2 to 5 and r from .05 to 1.00 in .05 increments. **(A)** The median of the SampEn estimates for all the assessment periods as a function of r . There was a convergence of the different template lengths for r between .20 and .30. **(B)** To verify the point of convergence, we computed the variance of the SampEn estimates for different template lengths relative to the mean at each value of r . Expanding the region of interest (i.e., $.2 > r < .3$) accentuated the differences between SampEn estimates and confirmed convergence of r around .20 and .25. At $r = .2$, the variance was already $< .001$, suggesting convergence from that point. **(C)** The median of the standard error of SampEn for all assessment periods as a function of r . SampEn estimates for $m = 2$ had consistently the lower error. **(D)** Standard errors were converted to percentages of their corresponding SampEn estimates. The standard error was still lowest for $m = 2$ and similar for $r = .2$ (.011, 5.55%) and $r = .25$ (.009, 6.08%). Therefore, we selected $m = 2$ and $r = .2$ to be more conservative and to reduce the risk of inflating the number of template matches.

Supplementary Figure S2



Supplementary Figure S2: Joint Angles. Inference results from Statistical parametric mapping (SPM) one-way repeated measures ANOVA analyses between Times (pre-test, post-test, post-24h, and post-48h) at each protocol (moderate- and high-intensity run and control). No differences were observed between times for all joint angles. Left column: moderate-intensity protocol; Middle column: high-intensity protocol; Right column: control protocol; First row: ankle angles; Middle row: knee angles; Third row: hip angles.

Supplementary Figure S3



Supplementary Figure S3: Coordination. Inference results from Statistical parametric mapping (SPM) one-way repeated measures ANOVA analyses between Times (pre-test, post-test, post-24h, and post-48h) at each protocol (moderate- and high-intensity run and control). No differences were observed between times for both relative phase angles (i.e., coordination). Left column: moderate-intensity protocol; Middle column: high-intensity protocol; Right column: control protocol; First row: ankle-knee relative phase angles; Last row: knee-hip relative phase angles.

5 ESTUDO 2

To be submitted to the British Journal of Sports Medicine

Article Type: Original Article

Changes in joint and coordination regularity following running distinguished runners who sustained an injury within six-months

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Abstract

Background: Running induces fatigue and changes in joint and coordination patterns, which is associated with injuries. Running-related injuries are multifactorial processes often resulting from the inability to overcome and recover from a repeated demand imposed during exercises. This study investigated whether acute and prolonged changes in joint and coordination regularity during a single-leg squat task following running at different intensities distinguished runners who sustained an injury within six months from those who did not. **Methods:** Thirty healthy recreational runners were evaluated pre, post, 24h, and 48h during a 60-second single-leg squat task after running at moderate (60min, 65%VO₂max) and high intensity (4x15min, 85%VO₂max) or rest (i.e., control). After six months of the assessments, runners were divided into two groups based on whether they did or did not report injuries within this period. The percent change of joint (ankle, knee angles) and coordination (ankle-knee relative phase) regularity (multiscale entropy) were compared between groups (injured, non-injured), times (%Post, %Post24h, %Post48h), and protocols (moderate-intensity, high-intensity, control). Additionally, one sample t-test compared the percent change difference from zero for each group across times. **Results:** The injured group increased ankle-knee coordination regularity (reduced entropy) immediately after the moderate (-27.7%) and high intensity run (-25.8%), which maintained increased after 48h (-14.5%). The injured runners also increased knee regularity at 24h (-11.3%) and 48h (-10.9%) after the high-intensity running, while the non-injured increased coordination (-14.5%) and decreased ankle (12.6%) and knee (13.5%) regularity on the post-test. No changes were observed after the control protocol. **Discussion:** Runners who sustained an injury within six-months after assessments increased joint and coordination regularity and required more time to recover than non-injured runners. Monitoring changes within individuals during a functional task may provide valuable early warnings about a reduced adaptive and recovery capacity to deal with training and exercises.

Keywords: fatigue; single-leg squat; ankle; knee; entropy.

Introduction

Running is a common cause of exercise-related musculoskeletal injuries, with high rates of injuries being reported every year [1–5]. Musculoskeletal injuries are a multifactorial process often related to the inability to overcome and recover from the continuous demands imposed by training and exercises [6–8]. Sports activities, such as running, commonly lead to neuromuscular fatigue, which often induces changes in joint and coordination patterns [9–11]. Additionally, fatigue is associated with injury occurrence if recovery is incomplete [12,13]. However, studies investigating movement patterns as risk factors for running-related injuries [14,15] and the time to recover from exercise or fatigue [9,13,16] have provided inconsistent results. Recognizing that it is impossible to obtain sufficient information about the many factors related to injury occurrence, applying tools and concepts from complex dynamical systems could improve understanding of the role of movement changes in response to exercise and help forecast injuries [17].

Running-related injuries are linked to a diminished capacity to adapt to repeated stresses imposed over time [8]. Runners commonly vary the intensity of their training sessions (i.e., moderate- and high -intensity) [18,19], which can lead to various levels of fatigue and demand different times for recovery [6,20,21]. Neuromuscular fatigue can decrease muscle activation and strength and increase muscle damage, reducing the ability of the musculoskeletal system to resist internal and external perturbations [22]. Recovery is a time-related process of repairing the various biological systems to reestablish or exceed the existing functional capacity [6,23]. Thus, a sustained imbalance between the imposed demand and recovery time can overcome the individual's ability to deal with exercise and fatigue, eliciting qualitative changes and increasing the injury risk [6,7,24]. However, studies investigating the recovery time of the movement pattern after training or fatigue only evaluated short periods, between 20 min to 6 h post-exercise [9,13,16]. Since runners usually train every day or every other day, longer assessment periods, such as 24h and 48h, are needed to understand the recovery process between training sessions or games [25,26]. Additionally, the runner's ability to resist perturbations from exercise and fatigue is essential to lowering injury occurrence [17]. Therefore, acute or prolonged altered movement patterns resulting from running in different intensities may reveal poor adaptive or recovery capacity and distinguish groups of runners with an increased risk of injury.

Human movement results from nonlinear interactions between the many elements and systems (e.g., neuromuscular, cardiorespiratory, physiological) that self-organize to produce macroscopic behaviors (e.g., coordinated movements to complete a task) spanning multiple levels (e.g., inter-muscular coordination or joint coordination) [27–30]. Identifying

macroscopic variables (i.e., order parameters) that characterize distinct physiological states (e.g., fatigue or injury status) is challenging but critical to developing assessments to investigate how movement evolves and adapts in response to perturbations, such as exercise and fatigue [17]. Although performance (e.g., number of repetitions), biomechanical (e.g., muscle strength and activity), and physiological (e.g., VO_2 max) variables are commonly used as markers to determine the influence of exercise on injury risk, they provide insufficient information about the interactions among biological systems [14,15,30]. Considering that the emerging movement constrains the behavior and interactions among the parts (e.g., joints), the time-dependent changes in the movement's pattern or structure (i.e., the movement dynamics) may provide information into the individual's physiological state. Therefore, instead of measuring individual factors related to injury, examining changes in variables that reflect the movement dynamics in response to exercise and fatigue could provide better insights into injury status [17].

To obtain information about movement dynamics after exercise and fatigue, joint angles and joint relative phase angles (i.e., joint coordination) have been analyzed with nonlinear measures, such as entropy [9–11]. Entropy measures quantify the amount of uncertainty or irregularity of a signal, where lower and higher entropy are associated with more regular or irregular behavior, respectively [31]. Specifically, increased regularity (i.e., reduced entropy) is commonly interpreted as a more predictive and less adaptive behavior [32]. For instance, increased regularity has been observed in injured individuals or with injury history compared to uninjured participants [33–37]. Thus, the same exercise that could induce changes in one group (e.g., injured-prone individuals) may not change the movement dynamics in another group (e.g., non-injured). Therefore, assessing exercise-induced changes in movement dynamics may distinguish runners with reduced adaptive capacity and indicate imminent injury [29].

Squatting is the foundation for many sports-related tasks, such as jumping and running, and is commonly used as part of training and rehabilitation sessions [38–41]. The single-leg squat task is a functional task that requires coordination across the ankle, knee, and hip joints to maintain balance with a reduced base of support [38,42]. The single-leg squat task has been used to inform about the physical condition of athletes, such as screening for injury risk, readiness to return to play, and distinguishing currently injured from non-injured participants [39,40,43]. Most studies have evaluated performance (e.g., number of repetitions, time, and speed) and biomechanical (e.g., peak of knee valgus) variables of the single-leg squat from a small number of repetitions [38,40,42]. Because sports activities impose cyclical demands and people can perform the same task in different ways [44], variables that describe

the structure of the movement during longer periods (more cycles) are needed to investigate the influence of training intensity on movement dynamics.

To predict future injuries, it is necessary to identify higher-order variables (order parameters) that characterize distinct states (e.g., joint and coordination regularity during a functional task), establish protocols to capture the time evolution of the order parameter (immediate and prolonged changes following running protocols at different intensities) and select adequate methods to analyze those dynamics and forecast future states (i.e., entropy measures) (Fonseca et al., 2020). Therefore, this study investigated whether changes in joint and coordination regularity during a single-leg squat task immediately, 24h, and 48h after running protocols at different intensities distinguished recreational runners who sustained injuries within the following six months from those who did not. Our hypotheses were: (1) Joint and coordination patterns would become more regular during the single-leg squat test in both groups immediately after the running protocols. Specifically, running-induced increased joint and coordination regularity would be greater in injured than non-injured runners; (2) Individuals who sustained injuries within six months would take longer to recover from the running-induced changes in joint and coordination regularity compared to the non-injured individuals; (3) After the higher the running intensity, there will be a greater reduction in entropy (increased regularity) and the longer recovery time in joint and coordination regularity during the single-leg squat test; (4) No differences between groups would be observed in the pre-test; and (5) No changes between groups or assessment times would be observed when individuals were not exposed to a running protocol (i.e., control condition).

Methods

Participants

Thirty-three recreational runners were recruited for this experimental, prospective study. The inclusion criteria were: (1) adults between 18 and 60 years old; (2) regularly running a minimum of 20 km/week for at least six months; and (3) being currently without injuries. An injury was defined as musculoskeletal pain or discomfort resulting in reduced or restricted training volume for seven days or three consecutive training sessions or requiring professional health care assistance [45]. The runners were instructed to maintain the training routine of the previous month (volume, pace, and intensity) until the end of the assessments. The participants were excluded if they could not complete the protocols or the single-leg squat task, failed to follow the instructions or attend all assessments, and presented pain or discomfort during the experiments. Two runners were excluded for having pain during the assessment and another failed to continue attending the assessments. A third participant

completed the study but was excluded because of data loss due to technical issues. This study was approved by the University's Ethics Committee (CAAE: 39729120.2.000.5149), and all participants provided informed consent after being instructed about the study.

Procedures

The participants reported their training routine (i.e., average pace, volume, and number of weekly training sessions), running experience, and previous injuries in the past six months. The study consisted of four weeks of testing, three different protocols, and a reassessment survey six months after the last evaluation (Figure 1). The protocols consisted of running at moderate and high intensities and a control protocol (no exercise).

During the first week, two visits were necessary to practice the single-leg squat test and estimate the maximum oxygen volume consumed ($\text{VO}_{2\text{max}}$). A pilot study indicated that two days of practice were needed to minimize the learning effects of the single-leg squat test. Over the following three weeks, the participants completed three consecutive visits per week. The first visit of each week consisted of performing the single-leg squat test before (pre-test) and immediately after (post-test) a protocol. During the second and third visits, the runners repeated the single-leg squat test 24h (post24-test) and 48h (post48-test) after each protocol. All participants completed all protocols in a random order, one per week.

After six months following the last assessment, participants completed a follow-up injury survey. The runners reported whether they sustained an injury after completing the study and their average volume and pace for the past six months. The runner who suffered an injury also reported the location (structure and segment), when it occurred, if the injury impacted their training routine (reduced or restricted their training volume) and if professional health care assistance was needed. Participants were stratified into two groups based on injury status (i.e., injured and non-injured).

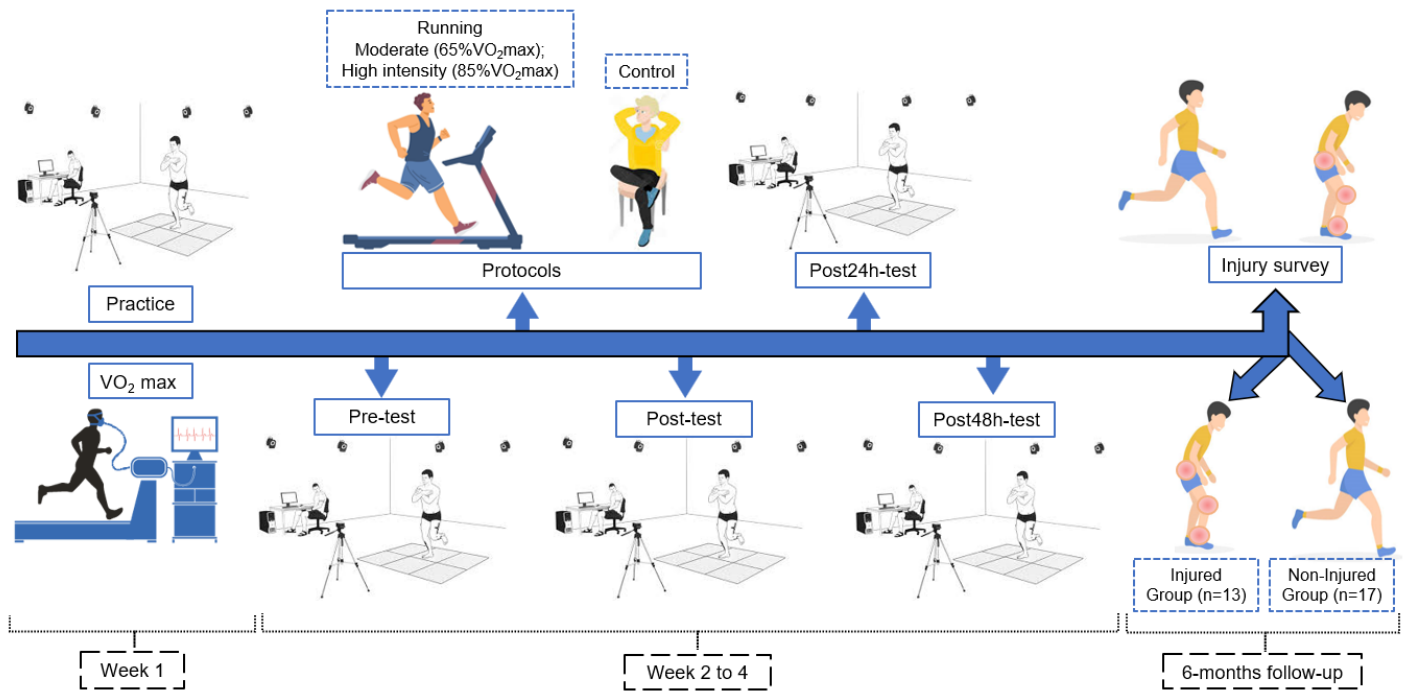


Figure 1: Study timeline. Participants were evaluated for four weeks. Two visits of testing were completed during the first week (Week 1) to collect intake information, practice the single-leg squat test, and perform the VO₂max test. During Weeks 2 to 4, the participants performed three protocols (running in moderate and high-intensity and control protocols) in randomized order, and the single-leg squat task was performed during pre-, post, post24- and post48h-tests. After six months of assessment, the participants responded to an injury survey and were divided into two groups (i.e., injured and non-injured). VO₂max: Maximum volume of oxygen consumed.

Single-leg squat test

The single-leg squat test consisted of 60-s uninterrupted squats at self-selected speed. Participants were instructed to stand barefoot over their dominant leg (i.e., preferred leg to kick a ball) with the foot perpendicularly aligned to a screen in front of them and hands crossed behind their heads (Figure 2). A screen with two horizontal lines (top and bottom targets) separated vertically by 30 cm was positioned in front of the participants. The distance between the participant and the screen was adjusted to ensure that 40° of knee flexion peak angle was required to complete each squat repetition. The amount of knee flexion was defined based on previous studies [38,39,43,46] and our pilot study. Therefore, the test was challenging, but it was feasible to perform uninterruptedly for 60 seconds. A laser pointer was attached to a rigid cluster positioned above the knee parallel to the ground and aligned with the greater trochanter. The screen's vertical position was adjusted so the laser was centered on the lower target with the knee extended. The single-leg squat test was adapted from Cardoso et al. (2021).

The runners were instructed to flex and extend their dominant lower limb, keeping the contralateral foot off the ground and the trunk upright. To complete the task, the participants had to continuously move the laser from the lower to the upper targets (i.e., knee extended

and flexed, respectively) and only reverse the direction after the laser contacted the target. The rate of perceived exertion (RPE) was assessed before and after each single-leg squat test using a modified Borg RPE scale with values of 0-10 [47,48]. If the participant moved their dominant foot or hands out of position or touched the stance leg or the ground with the non-dominant leg, the test was stopped and repeated. To avoid a secondary confounding source of fatigue, the participants rested for five minutes or until they returned to their initial RPE if a new trial was needed for pre-, post24-, post48- and control tests. After the running protocols (i.e., post-test), no rest period was provided since the participants were already expected to be fatigued from running. To warm-up, a 30-second practice trial was completed before each day's first single-leg squat task.

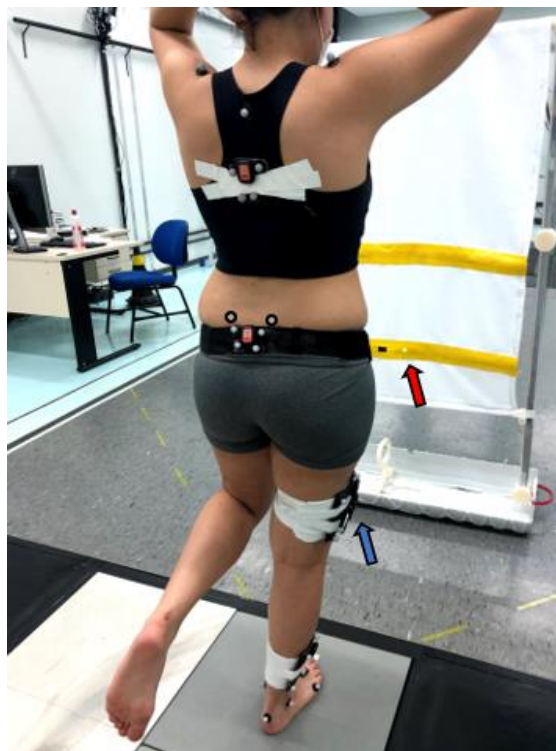


Figure 2. Single-leg squat task: Rear view of a person performing the single-leg squat task. Participants stood barefoot on their dominant leg in front of a screen with two horizontal targets. A laser was attached above the knee (blue arrow) and projected onto the screen (red arrow).

The single-leg squat task was assessed with a three-dimensional motion capture system (10 cameras, Oqus 7, Qualisys, Gothenburg, Sweden) at a sample rate of 120 Hz. Thirty-three retroreflective markers were placed on the foot, shank, thigh, pelvis, and trunk. Before each single-leg squat test, three static trials were collected with the participants in the upright position. Only the dominant leg was instrumented (Figure 2).

VO₂max

The VO₂max was assessed using a metabolic cart (HandyMET Clinic, MDI, Brazil), with an incremental treadmill protocol, with a fixed grade of 1% [49]. Participants were

familiarized with the treadmill and equipment. After a 3-minute warm-up at 8 km/h, the test started at an initial 9 km/h speed, increasing by 0.5 km/h every 30 seconds until exhaustion [49]. After exhaustion, the maximum speed was decreased by 60% in the first minute and further reduced by 5% each minute for 5 minutes [49]. The heart rate (HR) and RPE were assessed every minute during the test and the 5-minute recovery protocol. The peak of VO_2 during the test was considered a valid $\text{VO}_{2\text{max}}$ test if two or more of the following criteria were met: (1) $\text{HR} > 90\%$ of 220-age ; (2) $\text{RPE} > 9$; (3) respiratory exchange ratio > 1.1 ; (4) $\text{VO}_{2\text{max}}$ plateau; and (5) the person could not continue the test [50,51]. All tests were considered valid $\text{VO}_{2\text{max}}$. Thus, the $\text{VO}_{2\text{max}}$ was defined as the maximum VO_2 observed during testing. The $\text{VO}_{2\text{max}}$ was used to characterize the aerobic fitness of the participants and the speed corresponding to the $\text{VO}_{2\text{max}}$ was used to determine the intensity of the running protocols [52–54]. The HR_{max} during the test was also recorded and used to verify the maintenance of the intensity during the running protocols [53,55,56]. The participants were instructed not to engage in any exercise before the test.

Protocol

All runners completed three protocols randomly, one each week: running at moderate and high intensities and a control condition. A single-leg squat test was performed before (pre-test), immediately after (post-test), 24h (post24-test), and 48h (post48-test) after each protocol. The running protocols were performed on a treadmill without inclination. HR and RPE were assessed every 5 min to ensure the protocol intensity. The participants performed all four single-leg squat tests during the control protocol, but no exercise was performed. Instead, the participants rested between pre- and post-tests. Participants refrained from practicing physical activity for two days before each protocol to minimize the impact of recent training.

The running protocols were chosen according to past studies [52–55,57,58] and were meant to simulate a moderate and a high-intensity training session. The participants ran for 60 min on both running protocols, consistent with training sessions commonly reported in recreational runners [59]. Participants warmed up on the treadmill for five minutes at a self-selected speed before the running protocols started. HR and RPE were assessed every five minutes to verify the intensities of the protocols during the test [47,53,55,56,58].

The moderate-intensity protocol consisted of running uninterruptedly for 60 minutes at a speed corresponding to $65\%\text{VO}_{2\text{max}}$, which was considered a HR between 65 and 85% of HR_{max} , and the RPE between 6 and 8 [55,58,60]. The high-intensity running protocol consisted of four bouts of 15 min at $85\%\text{VO}_{2\text{max}}$ speed, with a 5-minute interval between

bouts to rest at their preferred speed. Pilot data and past findings (Kaufman et al., 2006) suggested that high-intensity running for durations exceeding 15 min leads to extreme fatigue. The HR and RPE should, respectively, remain higher than 85%HR_{max} and 8 to guarantee the high intensity of the protocol [53,55,56].

Data analyses

Kinematic data were analyzed using Visual3D (C-Motion, Inc., Rockville, Maryland, USA). Markers' linear displacements were filtered with a low-pass fourth-order Butterworth filter at a cutoff point of 6 Hz [61]. A biomechanical model and local coordinate system for each segment were created from a static trial. The Cardan sequence used was mediolateral, anteroposterior, and longitudinal. The ankle (angle between the foot and shank) and knee (angle between the shank and thigh) angles in the sagittal plane were calculated [62]. The 60-second time series of ankle and knee joints were exported to MatLab (MathWorks Inc., USA), and the joint and coordination regularities were calculated.

Joint Regularity

The regularities of the ankle and knee in the sagittal plane were calculated using Multiscale Entropy (MSE). MSE estimates the degree of randomness of a time series at multiple time scales (τ) using a coarse-graining procedure [63]. The coarse-graining procedure divides the original time series into non-overlapping windows by successively averaging consecutive data points into a new coarse-grained time series and calculating the SampEn for each time series [63]. For further details on the SampEn method and algorithms, Richman and Moorman (2000).

We adapted the criteria suggested by Ramdani et al. (2009) to select the entropy hyperparameters m (template length) and r (radius of similarity). The hyperparameters selected and used across all scales were $m = 2$ and $r = .20$. The length of the coarse-grained time series was the quotient between the length of the original time series (≈ 7200 points) and the number of scales ($\tau = 35$), where the shortest time series had at least 200 points (14^m with $m = 2$) [65]. The lower frequency that should be included in the MSE analysis was determined based on the length of the time series in seconds (60 s), the number of points in the last scale (200 points), and the hyperparameter m [65]. Thus, the ankle and knee angles time-series were filtered with a high-pass filter with a cutoff point of 0.5 Hz.

MSE analysis calculated the regularity of the filtered joint angles. MSE index was the area under the curve of SampEn estimates over 35 scales, MSE index. A higher MSE index (i.e., higher entropy) is related to more random dynamics or uncertainty about future

behavior, and a lower MSE index (i.e., lower entropy) indicates more regular dynamics or more predictable behavior [63,65]. The MSE index of the ankle and knee were compared between times (pre-, post-, post24-, and post48-test) for all protocols (moderate and high intensities run and control).

Coordination regularity

The coordination between the ankle and knee was calculated with a continuous relative phase (CRP) analysis based on the Hilbert transform [66], while regularity was measured using the MSE analysis described above. The filtered ankle and knee time-series in the sagittal plane during the 60-second trial were used to calculate the CRP before computing the entropy. The CRP quantified the phase relationship between ankle and knee joint angles (i.e., joint coordination) and generated a new signal representing the difference in the phase angles of the two original signals [66].

The CRP generated by the Hilbert transform was calculated based on the measured signal $x(t)$ and its Hilbert transform $H(t) = H(x(t))$. First, the amplitude of the data is centered around zero. Then, the real signal is transformed into a complex analytical signal [66,67]. The Hilbert transform $H(t)$ of $x(t)$ is the imaginary part of the analytical signal [66,67]. The phase angle at each point in time was calculated for each signal, and the CRP between the two signals was computed by subtracting the phase angles from each other, resulting in a new time series. If two segments are in-phase (0°), they are moving in the same direction, whereas in anti-phase coordination (180°), the segments move in opposite directions (Lamb and Stöckl, 2014).

The MSE analysis calculated the regularity of the CRP time series of ankle-knee relative phase angles in the sagittal plane, and the MSE index was the outcome used in the comparisons. A higher and lower MSE index (i.e., entropy) was related to a more random and regular coordination pattern, respectively.

Statistical Analysis

Characteristics of the injured and non-injured groups were compared using independent t-tests, with effects sizes estimated with Cohen's d and interpreted as small (.2), medium (.5), and large ($\geq .8$) [68]. Differences in task, dataset length, data cleaning, and hyperparameter selection can affect the measured values of entropy, which can impact results [69,70]. Therefore, joint and coordination regularity were compared based on the percent change of post-, post24- or post48 relative to the pre-test MSE index score:

$$\% \text{ Change} = ((\text{post or post24 or post48} - \text{pre}) / \text{pre}) \times 100.$$

This procedure produced within-person changes on a relative scale, which represented the percent change score from pre- to post-test (%Post), pre- to post24-test (%Post24), and pre- to post48-test (%Post48). Negative and positive values of the percent change score indicated that the Post, Post24, and Post48 MSE index was lower or higher than the pre-test value, respectively. Compared to a direct comparison of the measured values, evaluating within-person percent change provides more sensitive metrics for tracking outcomes over time and facilitates comparing results across different studies and populations or establishing clinically meaningful change [69]. The MSE index absolute values can be found in Supplementary Table S1.

The percent change from each variable (ankle, knee, and ankle-knee angles) was analyzed using a three-way mixed model analysis of variance (ANOVA) with Group (injured, non-injured) as a between-subjects factor, Time (%Post, %Post24, and %Post48) and Protocol (moderate-intensity, high-intensity, and control) as within-subjects factors. Post-hoc comparisons were made using Bonferroni correction. Additionally, to verify if the magnitude of relative changes in joint and coordination regularity were significant, we compared the groups' percent changes at each protocol against 0% using a one-sample t-test. To make sure that the groups were similar before the protocols, the absolute MSE index values from the pre-test were compared between Groups and Protocols with a two-way ANOVA. Partial eta squared (η^2_p) was computed to estimate the effect sizes for all ANOVA analyses and was interpreted as small (.01), medium (.06), and large ($\geq .14$) (Cohen, 1988). Statistical analyses were performed using SPSS Statistics version 21 (SPSS Inc. Chicago, IL, USA) with a significance level of 0.05.

Results

Participants

Thirty participants completed all three protocols and answered the injury survey six months later. Thirteen runners (43.3%) reported sustaining an injury between one and five months (average of 3.2 months) after completing the assessments and required reduction or interruption of training and assistance from a healthcare professional. Additionally, all reported injuries were running-related overuse injuries (e.g., fibular, patellar, and hamstring tendinopathies, piriformis and iliotibial band syndromes, shin splints, and plantar fasciitis) [8,71,72].

The injured ($n = 13$) and non-injured ($n = 17$) groups were compared based on age, sex, body mass index, VO_2 max, running experience, and training routine (i.e., average pace, volume, and number of trainings per week) (Table 1). No differences were observed between

groups in these characteristics. From the five runners who reported an injury six months before enrolling in the study, two were from the injured group – i.e., sustained a second injury in the following six months – and three were from the non-injured group – i.e., did not suffer another injury in the same period.

Table 1. Characteristics of the runners assigned to the injured ($n = 13$) and non-injured ($n = 17$) groups. Group means were compared using two-tailed independent samples t -tests with a significance level of $\alpha = .05$. Mean differences and 95% confidence intervals are reported. Effect sizes were estimated using Cohen's d .

Sample Characteristics	Injured	Non-injured	p-value	Mean difference (95% CI)	Effect size
	Mean (SD)	Mean (SD)			
Age (years)	40.46 (9.9)	36.35 (9.9)	0.27	4.11 (-3.4, 11.6)	.40
Sex (1-F / 0-M)	6 F / 7 M	5 F / 12 M	0.36	0.17 (-0.2, 0.54)	.47
Body mass index (kg/m ²)	23.55 (2.6)	24.3 (2.8)	0.47	-0.74 (-2.8, 1.3)	.28
VO ₂ max (ml·min ⁻¹ ·kg ⁻¹)	47.6 (5.0)	48.78 (6.8)	0.59	-1.2 (-5.8, 3.4)	.20
Running experience (years)	6.1 (10.9)	6.2 (5.6)	0.97	-0.1 (-6.4, 6.2)	.01
Number of training sessions (times/week)	4.15 (1.3)	4.29 (1.4)	0.78	-0.14 (-1.16, 0.88)	.10
Pace - Initial (min/km)	05:19 (0:36)	05:12 (0:51)	0.73	0:07 (-0:28, 0:39)	.13
Volume - Initial (km/week)	42.0 (22.3)	41.4 (26.4)	0.89	-1.21 (-19.9, 17.6)	.02
Pace - 6 months (min/km)	05:18 (0:33)	05:16 (0:43)	0.86	0:02 (-0:27, 0:32)	.06
Volume - 6 months (km/week)	33.0 (15.07)	51.6 (33.8)	0.055	-18.6 (-39.6, 2.1)	.71

SD – standard deviation; CI – confidence interval; F – female; M – male; Y – yes; N – no.

Joint regularity

MSE assessed ankle and knee regularity. The two-way ANOVA observed no differences on ankle MSE index at pre-test were observed between Groups ($F_{2,56} = 0.13$; $p = .718$; $\eta^2_p = .00$), Protocols ($F_{2,56} = 0.19$; $p = .827$; $\eta^2_p = .00$), or Group x Protocol interaction ($F_{2,56} = 0.27$; $p = .762$; $\eta^2_p = .01$). Similarly, no differences between Groups ($F_{2,56} = 0.04$; $p = .837$; $\eta^2_p = .00$), Protocols ($F_{2,56} = 0.99$; $p = .378$; $\eta^2_p = .03$) or interaction ($F_{2,56} = 0.94$; $p = .396$; $\eta^2_p = .03$) was observed for knee MSE index during the pre-test. The joint regularity percent change of the pre-test was compared between protocols, times, and groups. The three-way ANOVA revealed a Time effect on ankle and knee regularity, independently of protocol or group (Table 2). Post-hoc comparisons showed higher MSE index (i.e., reduced regularity) on %Post changes compared to %Post48h on ankle and %Post24h and %Post48h on knee

joints. Additionally, the analysis of the magnitude of changes relative to 0% demonstrated that only the high-intensity protocol induced significant changes (Figures 3 - B and E). Specifically, the ankle and knee entropy increased at %Post in the non-injured group, and decreased knee entropy was observed in the injured group at %Post24h and %Post48h. No significant changes were observed in the moderate or control protocols for joint regularity (Figure 3 – A, C, D, and F).

Table 2. Ankle, knee, and ankle-knee coordination means and standard deviation of Multiscale Entropy Index (MSE Index) percent change for groups, times, and protocols. The results of the three-way ANOVAs are reported, including F-values, p-values, and partial eta squared (η^2_p).

		Protocol																	
		Moderate									High						Control		
		Time			Injured			Non-injured			Injured			Non-injured			Injured		Non-injured
		Mean (SD)			Mean (SD)			Mean (SD)			Mean (SD)			Mean (SD)			Mean (SD)		Mean (SD)
Ankle (%)	%Post ^a	5.49 (16.9)	2.77 (20.4)	-3.13 (11.6)	12.61 (18.3)	-5.7 (10.5)	-3.54 (13.1)												
	%Post24h	-1.01 (22.8)	4.96 (20.9)	-7.54 (15.9)	0.92 (23.6)	-6.3 (11.2)	-3.29 (15.5)												
	%Post48h ^a	-9.7 (18.7)	-2.7 (19.1)	-9.68 (17.7)	-4.56 (16.7)	-5.54 (17.7)	-7.8 (20.5)												
Knee (%)	% Post ^b	6.66 (13.7)	2.8 (21.0)	-4.56 (13.0)	13.46 (17.8)	-3.29 (12.9)	-0.96 (12.2)												
	%Post24h ^b	-3.27 (18.72)	3.77 (26.1)	-11.28 (14.2)	1.35 (17.3)	-4.68 (12.5)	-1.53 (14.4)												
	%Post48h ^b	-7.66 (21.4)	-5.62 (19.2)	-10.87 (15.4)	0.77 (13.6)	-3.75 (17.2)	-6.3 (20.4)												
Ankle-Knee (%)	% Post ^c	-27.7 (25.7) ^d	-3.28 (38.6) ^d	-25.8 (17.4) ^e	-14.5 (21.4) ^e	-0.42 (15.5)	-6.25 (18.1)												
	%Post24h ^c	7.9 (22.9) ^d	8.64 (27.1) ^d	-5.3 (20.54) ^e	5.3 (16.9) ^e	-3.22 (24.7)	-2.29 (30.1)												
	%Post48h ^c	3.02 (33.1) ^d	15.06 (35.0) ^d	-11.2 (18.5) ^e	8.9 (25.5) ^e	-6.38 (31.2)	6.28 (28.6)												

Statistical effect																					
Time			Protocol			Group			Time x Group			Protocol x Group			Time x Protocol			Time x Protocol x Group			
<i>F</i> _{2,56}	<i>p</i>	η ² _p	<i>F</i> _{2,56}	<i>p</i>	η ² _p	<i>F</i> _{1,28}	<i>p</i>	η ² _p	<i>F</i> _{2,56}	<i>p</i>	η ² _p	<i>F</i> _{2,56}	<i>p</i>	η ² _p	<i>F</i> _{4,112}	<i>p</i>	η ² _p	<i>F</i> _{4,112}	<i>p</i>	η ² _p	
Ankle	7.98	.001*	.22	0.99	.376	.03	1.85	.184	.06	0.21	.815	.01	0.70	.499	.03	2.46	.05	.08	2.03	.094	.07
Knee	9.48	<.001*	.25	0.30	.741	.01	2.7	.112	.09	0.67	.512	.02	1.82	.171	.06	2.18	.076	.07	1.35	.255	.05
Ankle-Knee	17.3	<.001*	.38	0.96	.390	.03	6.74	.015*	.19	1.66	.199	.06	0.59	.557	.02	3.42	.011*	.11	1.53	.199	.05

SD – standard deviation; * - statistical significance ($p < 0.05$). Positive values and negative values indicate increased and decreased entropy relative to pre-test, respectively. ANOVA statistics are rounded to two decimals. Post-hoc with Bonferroni adjustment revealed a difference in: a – Time: %Post > than %Post48h ($F = 7.291$; $p = .003$; $\eta^2_p = .35$); b - Time: %Post > than %Post24h and %Post48h ($F = 9.109$; $p = .001$; $\eta^2_p = .40$); c - Time: %Post < than %Post24h and %Post48h ($F = 11.931$; $p < .001$; $\eta^2_p = .47$); d, e - Time x Protocol: only the running protocols were different in time - Moderate ($F = 10.084$; $p = .001$; $\eta^2_p = .43$) and High ($F = 7.505$; $p = .003$; $\eta^2_p = .36$).

Coordination regularity

Ankle-knee relative phase regularity (MSE index) was compared on pre-test, percent change, and difference from 0%. No significant difference MSE index was observed during pre-test between Groups ($F_{2,56} = 2.06$; $p = .163$; $\eta^2_p = .07$), Protocols ($F_{2,56} = 0.1$; $p = .758$; $\eta^2_p = .00$), or Group x Protocol interaction ($F_{2,56} = 0.73$; $p = .40$; $\eta^2_p = .03$). The percent change analysis demonstrated a Time, Group and Time x Protocol effect on three-way ANOVA (Table 2). Specifically, reduced entropy was observed on %Post compared to %Post24h and %Post48h, the injured and non-injured groups were different independently of time and protocol, and there were only differences between times during the running protocols (i.e., moderate and high intensities protocols). That is, no changes were observed during the control protocol across times. Moreover, during the moderate-intensity protocol, only the injured group changed significantly immediately after the running protocol (Figure 3-G). During the high-intensity protocol, both groups reduced entropy on %Post, but only the injured group demonstrated an increased regularity on %Post48h (Figure 3-H). No significant changes were observed during the control protocol in both groups and times (Figure 3-I).

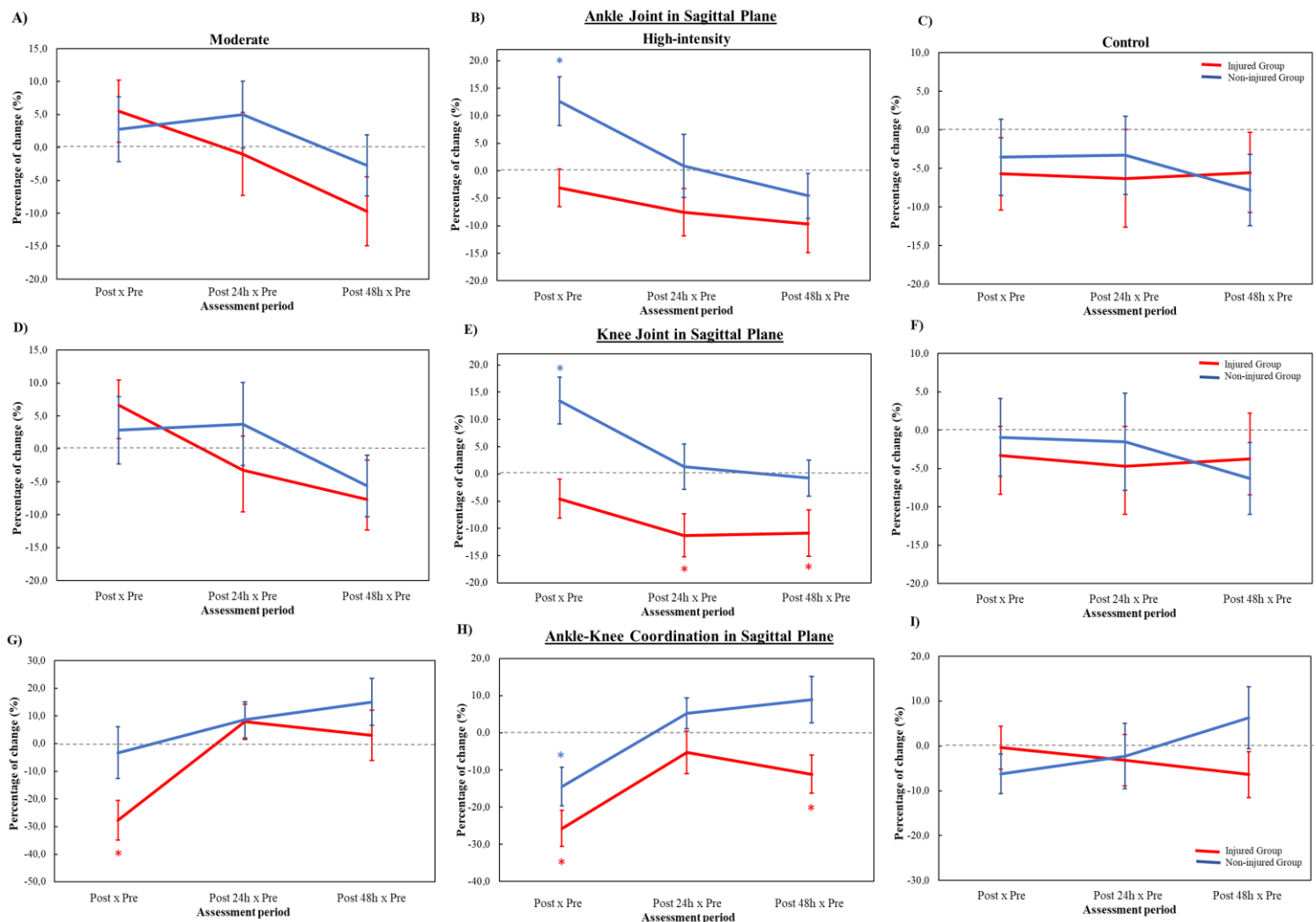


Figure 3. Difference from 0% - Multiscale entropy percent change means and standardized error (y-axis) relative to assessment period (x-axis) on ankle joint (A-C), knee joint (D-F), and ankle-knee coordination (G-I). **B)** Non-injured group increased ankle entropy on the post-test at high-intensity protocol ($t_{(28)} = 3.30$, $p = .003$). **E)** Non-injured group increased knee entropy on post-test ($t_{(28)} = 3.49$, $p = .002$), while the injured group decreased entropy at post24 ($t_{(28)} = 2.54$, $p = .017$) and post48-test ($t_{(28)} = 2.72$, $p = .011$) in response to the high-intensity protocol. **G)** Only the injured group reduced entropy immediately after the moderate-intensity protocol ($t_{(28)} = -2.96$, $p = .006$). **H)** Both groups significantly reduced entropy on the post-test of high-intensity protocol (injured: $t_{(28)} = -4.697$, $p < .001$; non-injured: $t_{(28)} = -3.03$; $p = .005$), but only the injured group remained with reduced entropy on post48-test ($t_{(28)} = -2.186$; $p = .04$). No differences from 0% were observed on moderate intensity at ankle (**A**) and knee (**D**) joints, or in control protocols (**C**, **F**, **I**). Left column - moderate-intensity running protocol. Middle column - high-intensity running protocol. Right column - control protocol. Red lines - injured group. Blue lines - non-injured group. * - significant difference from 0% ($p < 0.05$).

Discussion

This study investigated changes in joint and coordination regularity during a single-leg squat task immediately, 24h, and 48h after running at different intensities in recreational runners who became or were not injured within six months following the assessments. As hypothesized, the running protocols induced joint and coordination regularity changes in both groups, with greater changes observed in the injured group. As partially predicted, ankle-knee coordination became more regular in both groups immediately after the high-intensity protocol. In contrast, only the injured group reduced entropy after the moderate-intensity protocol. However, no changes were observed in joint regularity in the injured group, while the non-injured group increased ankle and knee entropy (i.e., less regular) after high-intensity protocol. As hypothesized, the higher running intensity led to greater changes and recovery time in joint and coordination regularity. Only the high-intensity running produced joint and coordination regularity changes that persisted for 24 and 48 hours in the injured group. No prolonged changes in response to running protocols were observed in the non-injured group. Additionally, both groups had similar entropy values before the protocols (pre-test), and no changes were observed during the control condition. Therefore, runners who did and did not sustain an injury within six months were distinguished by acute and prolonged changes in joint and coordination regularity after the running protocols.

Changes in joint coordination regularity were different between injured and non-injured groups following moderate and high-intensity running protocols. The three-way ANOVA showed that ankle-knee coordination entropy differed between groups across times and protocols. However, changes among times only happened after the running protocols (i.e., no changes after the control condition). Immediately after the moderate-intensity protocol, only the injured group decreased ankle-knee entropy (Figure 3-G). Individuals with reduced capacity (e.g., injured, diseased, and older individuals) tend to adopt more regular

coordination patterns, which is commonly interpreted as a less adaptive behavior compared to healthy individuals [35,73,74]. For instance, increased regularity of center of mass acceleration was observed in response to running-induced fatigue only in individuals with a priori reduced capacity (i.e., history of injury) [34]. An intensity around 65% of VO_2max can be considered a preferred exercise intensity by sports participants [55]. Still, running at moderate intensity can induce some neuromuscular fatigue [6,20,21]. Since overuse injuries (e.g., running-related injuries) are related to a lower capacity to adapt to the demand imposed by training over time [8,17], runners who sustained an injury may have a reduced capacity to adapt to exercises even in their habitual intensity. Therefore, the ability to withstand the exercise's demand from exercise appears to be related to forthcoming injury [17].

The high-intensity protocol produced changes in joint and coordination regularity in both groups. Comparing the changes against 0%, both groups reduced ankle-knee entropy on %Post (Figure 3-H). The high-intensity run may have decreased the capacity of runners to deal with task demands [6,20,21], which can be associated with a reduction in adaptability following fatigue-inducing exercise [75,76]. Changes in coordination patterns during the single-leg squat task can be interpreted as a compensatory strategy to accomplish the task [42]. Moreover, changes in coordinative patterns may constrain the available degrees of freedom, which may induce the emergence of different solutions for the same task [27,28,77]. Thus, both groups adopted more regular coordination to accomplish the single-leg squat task immediately after a higher-demand exercise. However, the injured group presented lower ankle-knee entropy after 48 hours compared to the pre-test. In addition, injured runners had reduced knee entropy on %Post24 and %Post48h following the high-intensity protocol. These results indicate that injured runners did not recover their joint and coordination regularity following exercise, suggesting that consequences of neuromuscular fatigue are still present after 48h. Prolonged effects of high-intensity exercise are associated with muscle damage and inflammatory responses of muscles and connective tissues within 12h, reaching a peak after 48h, which can alter the muscle's temporal recruitment patterns, changing muscle coordination and movement patterns [22,78,79]. This late inflammatory response occurs especially when the demand is above the musculoskeletal system's capacity [78,79] and seems to be signaled by the prolonged increase in joint and coordination regularity in the injured group. Therefore, runners who sustained an injury required more time to recover than non-injured runners, which may suggest a reduced adaptative capacity of these individuals to deal with fatigue-inducing exercise before the injury occurs.

Additionally, the decreased ankle-knee coordination entropy in the non-injured group was accompanied by an increased entropy at the ankle and knee immediately after the high-

intensity protocol. Similarly, increased joint entropy was observed following an induced-fatigue protocol in healthy runners, which was interpreted as an adaptative solution of the motor system in response to fatigue to accomplish the task [9]. However, no study investigated exercise-induced changes in both joint and coordination entropy. Here, the non-injured group decreased ankle-knee coordination entropy while increasing ankle and knee entropy immediately after the high-intensity protocol. Although the non-injured group increased coordination regularity in response to a high-intensity exercise, this seems to be compensated by a decrease in both joint regularities. Higher entropy can be associated with a less constrained and more adaptable behavior [80]. Individuals with more adaptable behavior self-organize to optimize their task performance [44]. Thus, the runners who did not become injured seem to adopt a less constraint and more adaptable behavior in the joints to compensate for the more constraint coordination induced by the high-intensity run. To confirm this conjecture, we ran a correlation analysis between the percent change in ankle-knee relative phase entropy and the sum of the percent change in ankle and knee entropy on %Post following the high-intensity protocol. We opted to sum the ankle and knee percent change in entropy because both joints behaved similarly in %Post (Figure 3 – B and E). Changes in ankle-knee entropy (%Post) were inversely and highly correlated with changes in joint entropy in the non-injured group ($p < .001$, $r = -0.85$) (Supplementary Figure 1). In contrast, no correlation was found between joints and ankle-knee entropy in the injured group after the high-intensity protocol on %Post ($p = .84$, $r = -0.1$), %Post24h ($p = .16$, $r = -0.4$) or %Post48h ($p = .50$, $r = -0.2$). Therefore, non-injured runners demonstrated different movement dynamics compared to injured runners, which appear to be related to an ability to mitigate the deleterious consequences of exercise-induced fatigue and reduce the occurrence of injuries [17,20].

Limitations

This study has a few limitations. Musculoskeletal injury is a multifactorial process that could be influenced by different factors. However, the groups had similar characteristics (e.g., age, sex, VO_2max), previous injuries, and training routine (i.e., weekly volume and pace). For instance, six months after assessments, the injured group reported a decrease in their weekly training volume of 21.4%, while the non-injured group increased by 24.6% relative to the initial condition. This data suggests that the reported injuries were unrelated to increased training volume. Moreover, this study did not include physiological variables (e.g., muscle activity and inflammatory cells) that may be affected by fatigue and injury, which could be considered in future studies. In addition, all injuries reported were running-related injuries commonly observed in runners [1,8,71,72,81] that are mainly related to a lower

capacity to adapt to repeated stresses imposed over time (Hreljac, 2005). Therefore, this approach may provide early insights into the individual's ability to respond to exercises performed in different intensities that could be related to an increased risk of injury.

Finally, the changes observed in response to running protocols during the single-leg task may not be applied to a different task. Distinct tasks impose different demands and coordination patterns that could be affected by exercise [82,83]. However, we proposed a simple, fast, and reliable single-leg squat test that can serve as a screening tool for different activities in clinical and sports environments. Therefore, we believe this study can improve the understanding of the impact of training on recovery time and changes in movement dynamics that could be associated with future injury occurrence. The study's small sample size may limit the generalizability and reduce its statistical power, so larger samples should be investigated to confirm our results. Still, this approach can help to warn of reduced adaptive capacity in sports participants and be used to develop preventive strategies for running-related overuse injuries.

Conclusion

Changes in joint and coordination regularity during the 60-s single-leg squat task following moderate and high intensities run distinguished runners who did and did not sustain an injury within six months of assessments. Runners who suffered an injury increased joint and coordination regularity and required more time to recover from the fatigue-inducing exercise than non-injured runners. In addition, the injured group changed the joint coordination regularity even after a protocol resembling habitual training intensity. These results suggest a reduced capacity of injured runners to adapt and recover from moderate and high-intensity activities before the injury occurs. In contrast, the non-injured group only reduced ankle-knee entropy immediately after the high-intensity protocol, which seemed to be compensated by an increase in ankle and knee entropies. Moreover, no differences were observed on the pre-test for all variables, and no changes were found after the control protocol. This study demonstrated the importance of examining within-subject acute and prolonged joint and coordination regularity changes after performing exercises of different intensities. Although joint entropy has revealed important information about exercise-induced changes, coordination entropy seemed more sensitive to distinguish groups of runners who will become injured in the near future. Therefore, monitoring changes within individuals and between training sessions using functional tests (i.e., single-leg squat task) may serve as a screening tool to provide valuable early warnings about reduced adaptive and recovery capacity of runners, which could be associated with future injury occurrence.

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.

Funding

The authors acknowledge the financial support offered by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil (CAPES, Finance Code 001) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil (CNPq, Process: 423731/2021-1).

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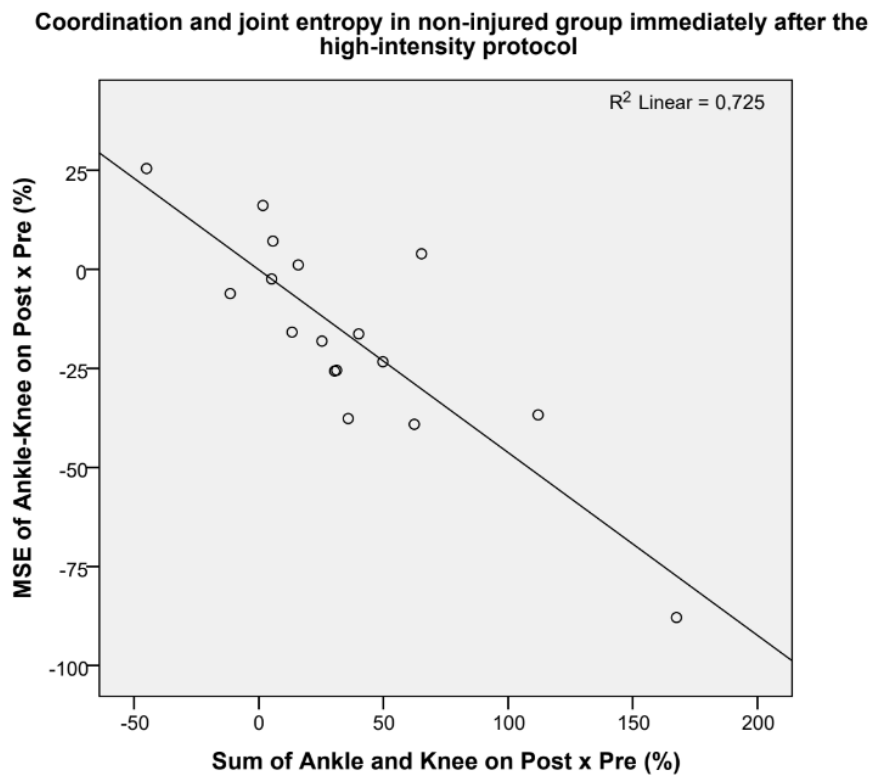
Supplementary Table S1

Table S1. Ankle, knee, and ankle-knee coordination means and standard deviation of Multiscale Entropy Index (MSE Index) values for groups, times, and protocols.

	Time	Protocol					
		Moderate		High		Control	
		Injured Group	Non-injured Group	Injured Group	Non-injured Group	Injured Group	Non-injured Group
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Ankle (bits ²)	Pre	23.5 (7.2)	25.1 (10.2)	23.5 (7.5)	23.6 (8.7)	23.1 (8.0)	24.7 (10.2)
	Post	24.03 (5.8)	24.8 (8.3)	22.5 (6.8)	25.7 (8.1)	21.5 (6.8)	23.5 (9.1)
	Post24h	22.6 (6.4)	26.05 (11.0)	21.2 (5.7)	22.96 (8.5)	21.2 (6.4)	23.6 (9.5)
	Post48h	20.7 (6.5)	23.9 (9.4)	20.3 (4.7)	21.9 (7.7)	21.4 (7.6)	21.9 (7.5)
Knee (bits ²)	Pre	19.6 (6.3)	21.5 (8.4)	19.7 (5.2)	18.8 (5.9)	19.3 (7.2)	19.6 (5.3)
	Post	20.5 (5.5)	21.1 (6.1)	18.6 (4.8)	20.7 (5.1)	18.2 (5.4)	19.5 (5.9)
	Post24h	18.5 (5.3)	21.4 (6.9)	17.3 (4.5)	18.7 (6.0)	17.8 (4.9)	19.3 (6.0)
	Post48h	17.5 (4.8)	19.6 (6.9)	17.2 (4.2)	18.3 (5.5)	18.03 (5.8)	18.1 (5.4)
Ankle-Knee (bits ²)	Pre	39.2 (7.3)	36.4 (9.7)	42.4 (6.2)	38.5 (6.8)	40.8 (6.6)	39.2 (9.0)
	Post	28.5 (11.5)	32.9 (8.9)	31.4 (8.2)	32.5 (9.1)	40.6 (8.1)	36.5 (10.2)
	Post24h	41.2 (5.4)	37.9 (7.9)	39.7 (8.4)	40.14 (7.7)	38.8 (8.7)	37.3 (10.9)
	Post48h	38.6 (7.9)	39.8 (8.6)	37.3 (8.5)	41.3 (9.5)	37.3 (10.8)	39.8 (5.6)

SD – standard deviation.

Supplementary Figure S1



Supplementary Figure S1: Correlation. Pearson correlation between the percent change in ankle-knee relative phase Multiscale entropy (MSE) (y-axis) and the sum of ankle and knee MSE percent change (x-axis) during dingle-leg squat task on post-test relative to pre-test after a high-intensity running protocol in the non-injured group. Changes in coordination regularity are inversely correlated to changes in joint regularity in the non-injured group ($r = -0.854$; $p < .001$).

6 CONSIDERAÇÕES FINAIS

A presente tese de doutorado investigou a influência da intensidade da corrida e do tempo de recuperação na cinemática, o padrão coordenativo, e a regularidade dos membros inferiores durante uma tarefa de agachamentos unipodais e a relação com a ocorrência de lesões em praticantes de corrida. Para isso, a tese foi dividida em dois estudos. O primeiro estudo avaliou especificamente o efeito imediato e prolongado de diferentes intensidades de corrida na cinemática, padrão coordenativo e na regularidade dos membros inferiores. Já o segundo estudo investigou se as mudanças induzidas por protocolos de corrida em diferentes intensidades na regularidade articular e do padrão coordenativo eram capazes de distinguir corredores que se lesionariam em até seis meses após as avaliações. Em ambos os estudos nenhuma diferença foi observada no pré-teste ou após o protocolo controle, isto é, todas as mudanças foram induzidas pela corrida. No geral, ambos estudos mostraram que monitorar mudanças durante uma tarefa funcional, como o agachamento unipodal, pode fornecer informações precoces sobre a capacidade dos indivíduos em adaptar e recuperar de treinamentos e exercícios.

No estudo 1, observamos que corredores recreacionais apresentaram um padrão coordenativo dos membros inferiores mais regular imediatamente após correr em intensidades moderada e alta, mas nenhum efeito prolongado foi observado. Especificamente, a corrida diminuiu a entropia da coordenação tornozelo Joelho no plano sagital durante o teste de agachamento unipodal, mesmo sem esforço máximo. Nas articulações do tornozelo e Joelho, um aumento da regularidade foi observado após 48h, independentemente do protocolo. Demonstramos ainda, que a análise das curvas cinemáticas médias normalizadas pelo ciclo de agachamento, seja dos ângulos articulares ou da coordenação, não foi sensível para detectar o efeito da corrida sobre os padrões de movimento. Além disso, demonstramos que analisar como as articulações interagem ao longo do tempo (regularidade do padrão coordenativo) pode ser mais importante para avaliar mudanças no sistema musculoesquelético após o exercício do que avaliar as articulações. Em conclusão, o primeiro estudo mostrou que avaliar o efeito da corrida em diferentes intensidades na regularidade dos padrões coordenativos durante testes funcionais pode gerar informações valiosas para identificar as respostas do atleta aos treinos e exercício. Após o primeiro estudo verificamos a necessidade de mais estudos investigarem as mudanças imediatas e prolongadas induzidas por exercícios na regularidade de articulações e coordenações e a possível relação com a ocorrência de lesões no esporte.

Complementando o estudo 1, o estudo 2 mostrou que mudanças na regularidade articular e do padrão coordenativo durante a 60 segundos de agachamento unipodal após protocolos de corrida em intensidades moderada e alta distinguiram corredores que sofreram ou não uma lesão em até seis meses após as avaliações. Os corredores que sofreram uma lesão aumentaram a sua regularidade articular e do padrão coordenativo, e necessitaram de mais tempo para se recuperar do que os corredores não lesionados. Além disso, o grupo lesionado alterou a regularidade da coordenação articular mesmo após uma intensidade habitual de treinamento. Esses resultados sugerem que corredores que se lesionaram apresentam uma capacidade reduzida de adaptar e recuperar de atividades em diferentes intensidades antes da lesão ocorrer. Em contraste, o grupo de corredores que não se lesionaram apenas reduziu a entropia do tornozelo Joelho imediatamente após o protocolo de alta intensidade, o que pareceu ser compensado por um aumento nas entropias do tornozelo e Joelho no mesmo período. Este estudo demonstrou a importância de examinar as mudanças individuais da regularidade articular e coordenativa imediatamente após e no período de recuperação de treinos e exercícios em diferentes intensidades. Portanto, monitorar como os indivíduos mudam entre as sessões de treinamento usando testes funcionais (i.e., tarefa de agachamento unipodal) pode servir como uma ferramenta de triagem para avaliar e alertar de forma precoce sobre uma possível redução da capacidade adaptativa e de recuperação de corredores que pode estar associado à ocorrência futura de lesões. Dessa forma, espera-se que os achados da presente tese contribuam para entendimento sobre como avaliar o efeito de rotinas de treinamento e do tempo de recuperação do padrão de movimento de atletas, que podem informar sobre possíveis riscos aumentados de lesões.

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ANEXOS

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**PARECER CONSUBSTANCIADO DO CEP****DADOS DO PROJETO DE PESQUISA**

Título da Pesquisa: Recuperação física pós atividade e padrão coordenativo

Pesquisador: Sergio Teixeira da Fonseca

Área Temática:

Versão: 2

CAAE: 39729120.2.0000.5149

Instituição Proponente: PRO REITORIA DE PESQUISA

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 4.532.902

Apresentação do Projeto:

O objetivo do presente estudo é investigar a influência da recuperação após atividade física habitual sobre o padrão coordenativo dos membros inferiores. O presente trabalho é um estudo com etapas com características observacionais transversal e etapas com características experimentais do tipo ensaio clínico aleatorizado. A amostra será composta por indivíduos ativos fisicamente recrutados por conveniência na comunidade, com idade entre 18 e 50 anos e que não apresentem sintomas nos membros inferiores e pelve. Para caracterização da amostra será aplicado um questionário a cada participante com os seguintes dados: idade, peso, altura, prática esportiva, tempo de prática da atividade, dias e duração dos treinos, membro dominante na atividade esportiva, nível da atividade (competitiva ou recreativa), atividades extras realizadas, e histórico de lesões no último ano. A tarefa escolhida para captar a estrutura espaço-temporal do movimento dos indivíduos será o agachamento unipodal guiado por laser. A regularidade das séries temporais dos padrões coordenativos, do tornozelo, joelho, quadril e pelve, será calculada por meio da Entropia Amostral da fase relativa. Os dados cinemáticos serão avaliados quanto a normalidade, a confiabilidade da tarefa e validade dos instrumentos serão analisadas, e o efeito da atividade física habitual e do tempo de recuperação serão obtidos através da ANOVA mista (fator grupo x fator medidas repetidas), considerando nível de significância de 0,05. O presente estudo permitirá esclarecer o efeito da atividades física habitual (aquelas que não induzem falha mecânica por fadiga) e do tempo de recuperação no padrão de movimento, podendo ser um passo inicial

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Continuação do Parecer: 4.532.902

para identificar períodos de recuperação inadequados a demanda imposta, contribuindo com pesquisas futuras e auxiliando no planejamento e prática clínica de profissionais de saúde.

Objetivo da Pesquisa:

Objetivo Primário: Investigar a influência da recuperação após atividade física habitual sobre o padrão coordenativo dos membros inferiores. **Objetivo Secundário:** - Verificar a confiabilidade teste-reteste da tarefa de agachamento unipodal guiado por laser em sistema tridimensional de análise do movimento.- Validar os sensores inerciais em relação ao sistema tridimensional de análise do movimento, na análise da cinemática dos membros inferiores e pelve durante a tarefa de agachamento unipodal guiado por laser.- Avaliar o efeito imediato e crônico da atividade física habitual sobre a regularidade do padrão coordenativo dos membros inferiores considerando o tempo de recuperação em uma tarefa de agachamento unipodal guiado por laser- Avaliar o efeito imediato e crônico do aumento da intensidade da atividade física sobre a regularidade do padrão coordenativo dos membros inferiores considerando o tempo de recuperação em uma tarefa de agachamento unipodal guiado por laser.

Avaliação dos Riscos e Benefícios:

Segundo os autores:

Riscos: Caso o voluntário, apresente fadiga ou algum sintoma nos membros inferiores durante a coleta, atitudes como intervalos maiores de descanso e /ou interrupção do teste serão adotados dependendo da intensidade do sintoma. Além disso, sessões de crioterapia poderão ser oferecidas ao participante para alívio dos sintomas. Os voluntários serão instruídos sobre como proceder caso apresentem dores musculares tardia (até 48h após os testes). Dores musculares tardias tendem a passar após alguns dias sem necessidade de intervenção e a aplicação de crioterapia ou a realização de alongamentos leves podem aliviar os sintomas. Caso os sintomas persistam, os participantes deverão contatar os pesquisadores para melhor avaliação do caso. **Benefícios:** Não haverá benefícios diretos a participação do voluntário na pesquisa. Porém, os achados neste estudo poderão contribuir para a comunidade científica e para a prática clínica de profissionais de saúde. Além disso, caso os pesquisadores detectem alguma alteração relevante do seu padrão de movimento, o voluntário será avisado e receberá as devidas orientações.

Comentários e Considerações sobre a Pesquisa:

Pesquisa relevante para a área de conhecimento, com boa fundamentação teórica, vinculada a projeto de doutorado do Programa de Pós-graduação em Ciências da Reabilitação/UFGM. O projeto conta com financiamento próprio, não possui instituição co-participante. Todas as

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Continuação do Parecer: 4.532.902

modificações solicitadas para o TCLE foram atendidas pelo pesquisador.

Considerações sobre os Termos de apresentação obrigatória:

Todos os termos de apresentação obrigatória foram apresentados e encontram-se adequados.

Recomendações:

Todas as adequações solicitadas foram realizadas pelo pesquisador, o parecer é favorável aprovação do projeto.

Conclusões ou Pendências e Lista de Inadequações:

Somos salvo melhor juízo, favoráveis a aprovação do projeto.

Considerações Finais a critério do CEP:

Tendo em vista a legislação vigente (Resolução CNS 466/12), o CEP-UFMG recomenda aos Pesquisadores: comunicar toda e qualquer alteração do projeto e do termo de consentimento via emenda na Plataforma Brasil, informar imediatamente qualquer evento adverso ocorrido durante o desenvolvimento da pesquisa (via documental encaminhada em papel), apresentar na forma de notificação relatórios parciais do andamento do mesmo a cada 06 (seis) meses e ao término da pesquisa encaminhar a este Comitê um sumário dos resultados do projeto (relatório final).

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1646940.pdf	03/02/2021 08:12:32		Aceito
Projeto Detalhado / Brochura Investigador	Projeto_Doutorado_MarianaAquino_COEP_NovoTCLE.pdf	03/02/2021 08:09:06	Mariana Rodrigues Carvalho de Aquino	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	NovoTCLE_ProjetoDoutorado_MariAquino.pdf	03/02/2021 08:08:53	Mariana Rodrigues Carvalho de Aquino	Aceito
Recurso Anexado pelo Pesquisador	RESPOSTA_DILIGENCIAS_DO_PARECER DO CEP.pdf	03/02/2021 08:08:08	Mariana Rodrigues Carvalho de Aquino	Aceito
Declaração de Instituição e Infraestrutura	ParecerCamaraEEFFTO_MariAquino.pdf	31/10/2020 12:19:10	Mariana Rodrigues Carvalho de Aquino	Aceito
Folha de Rosto	folhaDeRosto_Projeto_MariAquino.pdf	23/10/2020 16:15:22	Mariana Rodrigues Carvalho de Aquino	Aceito
Declaração de Instituição e Infraestrutura	CartaAnuencia_Lam.pdf	19/10/2020 16:03:16	Mariana Rodrigues Carvalho de Aquino	Aceito

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Continuação do Parecer: 4.532.902

Situação do Parecer:

Aprovado

Necessita Apreciação da CONEP:

Não

BELO HORIZONTE, 09 de Fevereiro de 2021

Assinado por:

Crissia Carem Paiva Fontainha
(Coordenador(a))

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Fisioterapeuta

Endereço: MG, Brasil / Data de Nascimento: 04/01/1992 / Nacionalidade: Brasileira/ Gênero: Feminino

Idiomas: Português (nativa); Inglês (fluente).

Formação acadêmica

- **2019 – 2023 (Novembro 2023): Doutorado – Ciências da Reabilitação**
 - 2019 – 11/2023: Departamento de Fisioterapia – Universidade Federal de Minas Gerais (UFMG), Brasil.
 - 2022 – 2023: Departamento de Cinesiologia – University of Massachusetts (UMASS), EUA.
 - Projeto: O efeito da fadiga na recuperação e no padrão coordenativo de corredores recreativos.
 - Orientação: Dr. Sérgio T Fonseca e Dra. Juliana Ocarino (UFMG); Dr. Richard Van Emmerik (UMASS).
 - Bolsa: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES/ NIH-NIDCD (UMASS).
- **2017 – 2019: Mestrado – Ciências da Reabilitação**
 - Universidade Federal de Minas Gerais (UFMG), Brasil
 - Título: Influência da amplitude de movimento de dorsiflexão do tornozelo na cinemática e cinética dos membros inferiores durante a marcha.
 - Orientação: Dra. Juliana Melo Ocarino; Dr. Renan Alves Resende.
 - Bolsa: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES
- **2010 – 2017: Graduação – Fisioterapia**
 - Universidade Federal de Minas Gerais (UFMG), Brasil.
 - Título: Confiabilidade dos escores individuais e totais do Índice de Postura dos Pés para adultos e idosos.
 - Orientação: Dr. Renan Alves Resende; Dra. Paula Lanna Silva.

Experiência Acadêmica

- **University of Massachusetts – UMASS Amherst**
 - 2022 – June 2023: Pesquisador. Projeto: “Aging and Speech Perception in Complex Listening Environments: Balancing and Listening While Walking”. Grant: National Institutes of Health–NIH.
- **Associação Mineira de Reabilitação – AMR**
 - 2017 – 2020: Pesquisador; Orthotics for Humans Laboratory (OhLab); Projeto: “Órtese de impressão 3D para indivíduos com Paralisia Cerebral”. Grant: Ministério da Saúde (nº25000163653/2014-33).
- **Universidade Federal de Minas Gerais – UFMG**
 - 2020 – 2021: Professor; Departamento de Fisioterapia; Disciplina: Cinesiologia.
 - 2019 – 2022: Professor; Programa de Pós-Graduação em Ciências da Reabilitação; Disciplina: Sistemas de análise do movimento.
 - 2018 – 2019: Professor; Departamento de Fisioterapia; Disciplina: Fisioterapia aplicada a ortopedia.
- **Faculdade de Ciências Médicas de Minas Gerais – FCMMG**
 - 2022 – 2022: Professor; Programa de Pós-Graduação em Fisioterapia Aplicada ao Esporte; Disciplina: Terapia manual; Tema: Quiropraxia

- **Centro Universitário de Belo Horizonte – UniBH**
 - 2022 – 2022: Professor; Departamento de Fisioterapia; Disciplina: Terapia manual.

Experiência Clínica

- **The Unit**
 - 2021 – Atual: Fisioterapeuta. Pacientes ortopédicos, atletas de elite e recreacionais de diferentes esportes.
- **Confederação Brasileira de Ginástica - CBG**
 - 2020 – 2022 (contrato): Fisioterapeuta. Ginástica de Trampolim. Times júnior e sênior.
- **Confederação Brasileira de Esportes no Gelo – CBDG**
 - 2022 – 2023 (contrato): Fisioterapeuta. Curling. Times sênior feminino e masculino.
- **Prefeitura Municipal de Contagem, Minas Gerais – Brasil**
 - 2018 – 2022: Fisioterapeuta. Atletas de Ginástica de trampolim de 6 a 25 anos.
- **ProSports Fisioterapia**
 - 2017 – 2020: Fisioterapeuta. Pacientes ortopédicos, atletas de elite e recreacionais de diferentes esportes.

Patentes

- Aquino, Mariana RC; Lana, MRV; Fonseca, Sérgio T; Horta, Anderson A; Maia, Joana P.; Reis, Paulo RHG; Alves, Davi N. Ankle foot orthosis with an external propulsion system. 2020, Brasil. Patente: Inovação. Número: BR1020200154583. INPI. Depósito: 29 de julho, 2020.
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- Aquino, Mariana R C; Liddy, Joshua; Napoli, Dane; Fonseca, Sérgio; Van Emmerik, Richard; Busa, Michael. Changes to balance dynamics following a high-intensity run are associated with future injury occurrence in recreational runners. *Frontiers Network Physiology*. 2023. doi: 10.3389/fnntp.2023.1227861.
- Fonseca, Sergio; Souza, Thales; Aquino, Mariana R C; Castor, Camila; Carvalho, Renatha; Santos, Thiago; Okai-Nobrega, Liria; Resende, Renan; Ocarino, Juliana. Capítulo: Can Movement pattern's non-linear analysis reveal the status of the musculoskeletal system? *Progress in Motor Control*. 2023. ISBN: 9780443239878.
- Aquino, Mariana R C; Resende, Renan A; Van Emmerik, Richard; Souza, Thales R; Fonseca, Sergio T; Kirkwood, Renata N; Ocarino, Juliana M. Influence of reduced passive ankle dorsiflexion range of motion on lower limb kinetics and stiffness during gait. *Gait & Posture*. Em revisão. 2023.
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- Volpini Lana, Mariana R; Aquino, Mariana R C; Holanda, Ana Carolina; Emygdio, Elizabeth; Polese, Janaine. Clinical effects of robotic assisted gait training in speed, walking distance and functionality are maintained over the long term in individuals with cerebral palsy: A systematic review and meta-analysis. *Disability And Rehabilitation*. doi:10.1080/09638288.2021.

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- Lana, Mariana R. V; Aquino, Mariana R C. Chapter 2: Prothesis: Evolution and Innovation. *ENGENHARIA BIOMÉDICA: Tópicos Atuais e Avanços nas Diversas Áreas de Atuação*. 1ed.Carolina do Norte, EUA: Lulu Publishing, 2018, v. 1, p. 65-85.
- Guimarães, Igor; Volpini, Mariana; Aquino, Mariana; Cavaleiro, Jessé; Alves, Davi; Vimieiro, Claysson. Methodological Properties of Transcutaneous Electrical Nerve Stimulation Equipment Used for Analgesia in Humans: A Systematic Review. *SN Comprehensive Clinical Medicine*. 2021. doi:10.1007/s42399-021-00845-z.
- Lana, Mariana Volpini; Aquino, Mariana; Horta, Anderson; Reis, Paulo; Maia, Joana; Fonseca, Sérgio T. 3D printing orthosis with propulsion system increases pelvic rotation in gait of children with cerebral palsy. In: *The 6th World Congress on New Technologies, 2020, Prague, 2020*. doi:10.11159/icbb20.108.
- Lana, Mariana R V; Reis, Paulo Henrique R G; Horta, Anderson; Maia, Joana P; Aquino, Mariana R C; Rubio, Juan Carlos. Novel Plantar Surface Design of a Hinged Ankle Foot Orthosis Manufactured by 3D Printing. In: *The 6th World Congress on New Technologies, 2020, Prague, 2020*. doi:10.11159/icbb20.107.

Premiações

- 2023: Melhor apresentação (pôster): Changes to balance dynamics following a high-intensity run are associated with future injury occurrence in recreational runners. *Progress in Motor Control 2023, Roma – Itália*.
- 2021: Melhor apresentação oral: Stiffness of forefoot surface in ankle-foot orthosis influences the gait of children with Cerebral Palsy. *Congresso Brasileiro de Biomecânica 2021, Brasil*.

Habilidades técnicas

- Qualisys Track Motion (QTM) – Nível: avançado.
- Visual 3D (V3D) – Nível: avançado.
- SPSS Statistics – Nível: avançado.
- MATLAB – Nível: intermediário.
- Metabolic cart – Nível: intermediário.
- Microsoft office – Nível: avançado.

Certificações Clínicas

- 2019: Palmilhas ortopédicas biomecânicas.
- 2018: Quiropraxia clínica.
- 2018: Terapia manual.
- 2017: Terapia manual intramuscular - Dry needling.
- 2017: International dynamic taping.

Orientações

- 2022 – 2023. Coorientação estudo independente – Graduação em Cinesiologia. Aluno: Shih-Ting Kao. UMASS
- 2021 – Atual. Coorientador – Graduação em Fisioterapia. Dissertação: “Influence of fatigue on recovery and performance of the Counter Movement Jump”. Alunos: Rebeca Melo, Pedro Mello. UFMG.
- 2020 – 2022. Orientador – Especialização em fisioterapia esportiva. Dissertação: “Injuries differences between recreational and professional volleyball players”. Aluno: Gabriel Guerzoni. UFMG.
- 2020 – 2022. Orientador – Especialização em fisioterapia esportiva. Dissertação: “Influence of lower limb range of motion on sports performance”. Aluno: Ana Carolina Oliveira. UFMG.
- 2019 – 2022. Coorientador – Graduação em Fisioterapia. Dissertação: “Influence of musculoskeletal factor on dynamic knee valgus”. Alunos: Ana Carolina Tolomelli, Fabiane Silva. UFMG.