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様式3

論　文　内　容　の　要　旨

氏　名　（　　大西 和歩　　）	
論文題名	Digitized Climbing: Grade Estimation and Motion Generation for Sport Climbing with AI-Driven Modeling （クライミングのデジタル化: AI-Drivenなスポーツクライミングのグレード推定とモーション生成）

論文内容の要旨

A digital twin is a concept that involves replicating real-world products or phenomena in a digital environment and utilizing the information obtained from the replicated environment. The origins of digital twins can be traced back to the 20th century; however, advancements in computer-related technologies have led to a surge in attention in recent years. The development of digital twins is expected to enable foresight into future scenarios through simulations and to identify optimal decisions for actions to be taken moving forward. Here, enhancing the accuracy of simulations relies heavily on how effectively various real-world information can be digitized and integrated into the digital environment. In particular, successfully digitizing complex concepts such as human thought and movement is expected to enable more accurate simulations. Moreover, accumulating case studies of such efforts is expected to facilitate the realization of digital twins in new fields. Based on this perspective, the author focused on sports-particularly sport climbing-as a concept that includes complex elements such as human thought and movement.
Sports climbing is a sport in which participants ascend artificial walls from start to finish using artificial protrusions called “holds”. The path from start to finish is commonly referred to as a “problem” or a “route”. The author proposed an ideal example of a digital twin in sport climbing: a cycle that analyzes climbers’ movements, generates appropriately challenging problems to improve their skills, and supports their learning of the generated problems. To realize this cycle, the author focused on two essential elements - “difficulty classification of problems” and “motion generation”-as the main research areas.
First, the study on difficulty classification of climbing problems is explained. In sport climbing, the difficulty of a problem is typically determined subjectively by the person who sets the problem or the first climber to successfully complete it. Consequently, there is no standardized method for determining problem difficulty. This lack of consistency can lead to disadvantages, such as difficulty in accurately assessing one’s skill level. A standardized method for determining problem difficulty is therefore desirable. However, given the infinite variety of climbing problems, a universally applicable formulaic approach is impractical. To address this, the present study proposes a method for determining difficulty using deep learning. The proposed method introduces a metric called “hold difficulty”, which indicates the likelihood that a specific hold will be used in problems of a specific difficulty level. The model comprises two main parts: the first predicts the difficulty of holds used in a given problem, and the second combines the predicted hold difficulties with information about the arrangement of holds to output the overall problem difficulty. As a result, the model achieved a classification accuracy of 37.9% for hold difficulty (6-class classification) and 70.1% for problem difficulty (13-class classification), surpassing the performance of existing methods in classifying the difficulty of climbing problems.
Next, the study on motion generation is explained. Generally, the ability to generate realistic motions can enhance the sense of immersion in fields such as animation and gaming. In sport climbing, however, motion generation offers additional benefits. For instance, during the process of creating climbing problems, it is crucial to ensure that climbers do not adopt overly strenuous postures. By generating climbing motions in a simulation environment, such evaluations can be performed without physically setting holds on the wall. Furthermore, visualizing the problem from the generated motion’s perspective in a VR environment could enable climbers to form a more concrete image of their ascent. Given these potential benefits, this study explored motion generation. Since generating optimal motions for a humanoid is challenging due to the vast range of possible actions, this study employed deep reinforcement learning to tackle the motion generation problem. To validate the feasibility of motion generation, humanoids were tasked with climbing several problems in a simulation environment. First, the ability to generate human-like motions was examined. While some generated motions differed from human behavior, certain parts resembled realistic movements. Next, the study assessed whether motions suited to various body types could be generated. Humanoids of different heights were tasked with climbing, and each humanoid was observed to adopt strategies adapted to its height. Furthermore, climbing while minimizing hand load-a critical aspect of sport climbing- was incorporated into the learning process. The study demonstrated that it is possible to train humanoids to climb while reducing hand load. This research highlights the potential applications of motion generation and provides a foundation for future studies.
Overall, this study presented an example of a digital twin in the context of sport climbing, addressing the challenges of difficulty classification and motion generation required for its construction, and demonstrated the feasibility of the proposed method for building a digital twin.

様式 7

論文審査の結果の要旨及び担当者

<table>
<tr><td colspan="2">氏　　名　　（大西　和歩）</td></tr>
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論文審査の結果の要旨

本博士論文は，近年着目されるデジタルツインの概念を身体動作の評価に応用することを目的としている．物理空間とデジタル空間を双方向な連携は，リアルタイムの状態把握やシミュレーションを可能とし，複雑な現象を詳細に解析できるようになった．本研究では具体的なトピックとしてスポーツクライミングを取り上げ，デジタルツインによる環境や人間の動作生成を通じてスポーツクライミングにおける競技者の技能を向上させることを目指している．

本博士論文では大きく二つの課題に取り組んでおり，それぞれの成果は以下のとおりである．ひとつは，第3章で着目しているスポーツクライミングにおける課題の難度自動推定である．スポーツクライミングにおいては，登攀課題の難度は設定者の主観により決定されており，競技者間で統一された基準として存在していない．そこで本論文においてはホールド難度と呼ばれる指標を導入し，課題に用いられているホールド単位での難度予測を行ったのち，ホールドの配置情報と組み合わせることで，課題全体の難度を推定する手法を提案している．ホールド難度では6クラス分類問題において37.9%，課題難度では13クラス分離問題において70.1%の推定精度を達成し，優れた成果を示した．この課題の成果は論文誌にて発表された［大西ら，ホールド難度と配置を考慮したボルダリング課題の自動難度推定，日本バーチャルリアリティ学会論文誌，2022］．

もうひとつの課題は，第4章で着目したクライミングのモーション生成である．単に課題の難度を推定するだけでは実際の登攀動作を評価するには十分でないと言う点から着想し，深層強化学習を用いた登攀動作の自動生成に取り組んでいる．シミュレーション環境においてヒューマノイド型エージェントに登攀課題を解かせることで，人間らしい動作の獲得や体型の変化に適応した戦略を獲得することを目指している．また，スポーツクライミングにおいて重要な要素である手にかかる荷重の評価及び最小化といった要素を学習に組み込むことで，実際に生成される動作が登攀において実用的であり，かつ安全である可能性を示している．この課題に関連する成果は国際会議2件で発表された［K. Onishi et al., Generating Double Dyno Motion for Humanoid Agents in Simulated Bouldering Environment through Deep Reinforcement Learning, IEEE AIxVR2025 Workshop on AI and AR/VR for Exergaming, 2025］［K. Onishi et al., Climbing Motion Generation for Humanoid Agents through Deep Reinforcement Learning with Optimization Constraints, IEEE ICM2025, 2025］．

これらの成果は，スポーツクライミングにおけるデジタルツインの有用性や実現可能性を示しているとともに，スポーツクライミングに限らず従来の身体動作を伴う技能全体において長く課題となってきた評価の主観性の高さや，単一の動作生成手法の限界を突破する新たな可能性を提示しており，身体動作の評価や技能の伝承に情報科学分野からアプローチする道標となりうる．たとえばリハビリテーションやスポーツ全般の技術解析，さらにはエンタテインメント分野におけるリアルなキャラクタ動作の生成など，幅広い分野への応用が考えられる．よって，本論文は博士（情報科学）の学位論文として高い価値を有すると認める．