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研究課題名（和文）CFD simulations of fluid dynamics in sports science for better performance of athletes

研究課題名（英文）CFD simulations of fluid dynamics in sports science for better performance of athletes

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研究成果の概要（和文）：スポーツ中にアスリートの周囲で空気や水がどのように流れるかをシミュレーションすることは、考慮すべき要素が多く、非常に困難です。私たちは、コンピュータシミュレーションで現実の状況を精度よく模倣できる最先端のツールを開発しました。このツールは、複雑な形状や状況を正確に表現できるようにしたものと、動いたり変化したりする形状を扱う際にコンピュータプログラムをより効率的にするためのものです。この新しいツールを使うことで、水泳やスキージャンプといった現実のスポーツを、これまで不可能だった方法で研究することができるようになったのです。これにより、スポーツ科学や工学の分野で新たな発見や改善が期待されます。

研究成果の学術的意義や社会的意義
This advanced CFD framework enhances the understanding of real-world sports simulations, enabling improved performance analysis and optimized equipment design, ultimately benefiting both athletes and sports science by fostering innovation and facilitating data-driven decision-making.

研究成果の概要（英文）：Simulating how air or water flows around athletes during sports is quite difficult because of the many factors that need to be considered. We have created a cutting-edge tool that can mimic real-life conditions in computer simulations with good accuracy. This tool is a result of two major breakthroughs: one that can precisely represent complex shapes and situations, and another that makes the computer program more efficient when working with moving or changing shapes. With this new tool, we have been able to study real-life sports, like swimming and ski-jumping, in a way that was never possible before. This could lead to new discoveries and improvements in sports science and engineering.

研究分野：Computational Fluid Dynamics

キーワード：Biomechanics　Sport Fluid Dynamics　Immersed boundary method

１．研究開始当初の背景

Fluid dynamics is crucial in sports biomechanics, and Computational Fluid Dynamics (CFD) is a computer-based simulation technique used to analyze fluid flow systems. CFD is widely applicable and powerful, particularly in competitive sports such as sailing, swimming, rowing, and ski-jumping, where a 1-5% speed difference can make a significant impact on the athletes' performance. To predict athlete performance accurately, both experimental and numerical methods are required to account for the nuances of fluid dynamics in sports. While experimentation is the most common method used to obtain accurate values of hydrodynamic and aerodynamic forces, CFD is gaining popularity due to its relatively low cost, ease of usage, quick results, and ability to visualize quantities that are challenging to obtain through experiments, such as flow streamlines, wave profiles, and pressure distribution. CFD has become an indispensable tool for the analysis of aerodynamics and hydrodynamics in sports. However, analyzing fluid flow in sports where subjects are in continuous unsteady motion, such as dynamically changing postures and limb orientations, is complex and challenging.

２．研究の目的

Methods for CFD simulation of moving bodies in sports exist, but they come at a significant computational cost compared to simulations of fixed bodies. The dynamic grid approach involves mesh deformation to accommodate moving bodies, but deformed meshes lose mesh fidelity quickly, making the method less robust. Remeshing the grid can address this issue, but it incurs high computational costs, resulting in several times longer time-to-solution compared to fixed body simulations. The discrete forcing immersed boundary approach is well-suited for flow around fixed bodies with complex geometries, but it is slow for moving geometries due to the need for regenerating mesh-geometry intersection information at each time-step. Mesh-free methods, such as SPH and Vortex element methods, can simulate flow around moving bodies, but they are more suitable for low Reynolds number flows. In sports, Reynolds numbers can range between 10^5 and 10^6, which are too high for mesh-free methods to produce accurate results. To address these limitations, this research focused on the development of a scalable efficient and accurate numerical framework that can enable CFD simulation of sports under real-word conditions.

３．研究の方法

The following methods were developed in this project to aid CFD simulations of sports in real-world conditions.

(1) Higher accuracy immersed boundary method.

A method called Stencil Penalty approach-based Constraint Immersed Boundary (SPcIB) for modeling fluid-structure interactions (FSI) was developed. The SPcIB method addresses the challenge of accurately imposing the no-penetration velocity boundary condition at the immersed boundary (IB) surface in the original cIB formulation. This method introduces a corrective force term and utilizes a smoothness indicator-based stencil penalization to improve the modeling of zero-thickness surfaces. By redefining the discrete gradient operator using the WENO scheme-based smoothness indicator and selectively penalizing the gradient evaluation stencils that encounter pressure jumps, the SPcIB method enhances accuracy.

A one-sided Immersed Boundary (IB) method for modeling complex moving domain problems was also developed. It overcomes the limitations of standard IB methods by using Moving Least Squares (MLS) to construct one-sided regularized delta functions, which interpolate velocity from and spread force to only one side of the interface. This approach provides a stable and accurate solution that reduces memory footprint and allows for easy parallelization. The accuracy of the one-sided IB method is tested through various numerical experiments, including Taylor-Green vortex flow, Stokes' first problem, Impulsive flow over a cylinder, Impulsively started plate, Flow around an oscillating cylinder, Flow past a sphere, and Ahmed body. The proposed method showed improvements in accuracy by mollifying weights in both velocity interpolation and force spreading operators and adopting the original non-shifted MLS weights in the velocity interpolation operator.

(2) Lagrangian-Eulerian Framework for complex moving geometries.

We adopt a Lagrangian-Eulerian framework to enable dynamically moving and deforming complex geometries. To that end, we utilize a meshing methodology called the Building Cube Method (BCM) (Nakahashi, 2001) to represent the Eulerian mesh. The BCM involves dividing the computational domain into discrete blocks known as cubes. While these cubes can theoretically have varying edge sizes, for simplicity and consistency, we employ cubes with equal sides. This approach is commonly used in BCM applications, including this study. Depending on the specific needs of the problem, larger cubes are progressively subdivided into smaller cubes to create a hierarchical structure with layers of varying cube sizes.

The building CUBE Lagrangian data structure that enables efficient Lagrangian-Eulerian interpolation. The data structure is designed to store particle positions, velocities, and other relevant information for Lagrangian simulations. It is implemented using a parallel hash table with open addressing and linear probing, which allows for efficient parallelization and load balancing.

(3) Non-inertial frame of reference

In CUBE, the mesh is static and does not change with time, therefore it may not be possible to fully capture the dynamics of the fluid flow when the athlete's body is moving. One way to overcome this limitation is the use of non-inertial frame of reference. The non-inertial frame of reference approach in CFD is used to model fluid flows where the fluid and the computational mesh are both moving. This approach involves the use of a non-inertial reference frame that is co-moving with the fluid or the mesh. In this frame of reference, the fluid appears stationary, allowing the use of traditional CFD methods to solve the equations of motion.

The motion of a geometry is provided as input to the computational fluid dynamics (CFD) solver Cube by decomposing it into deformational and rigid velocity. The geometry's deformational velocity is imposed as a local velocity boundary condition on the flow to satisfy no-slip and no-penetration conditions on the jumper's body surface. The rigid velocity of the geometry is incorporated through the non- inertial frame of reference approach. Cube provides the resulting flow around the geometry and the aerodynamic forces acting on the geometry as output.

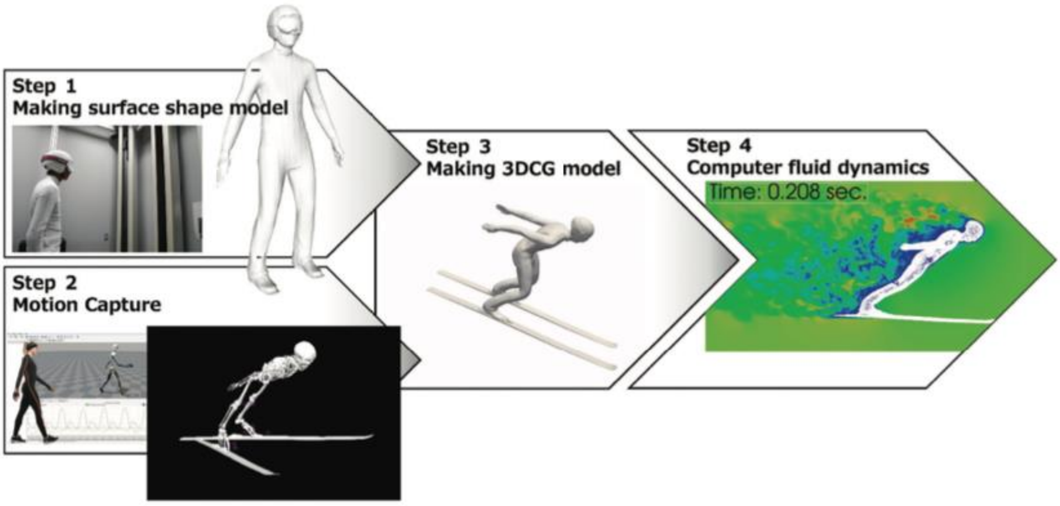
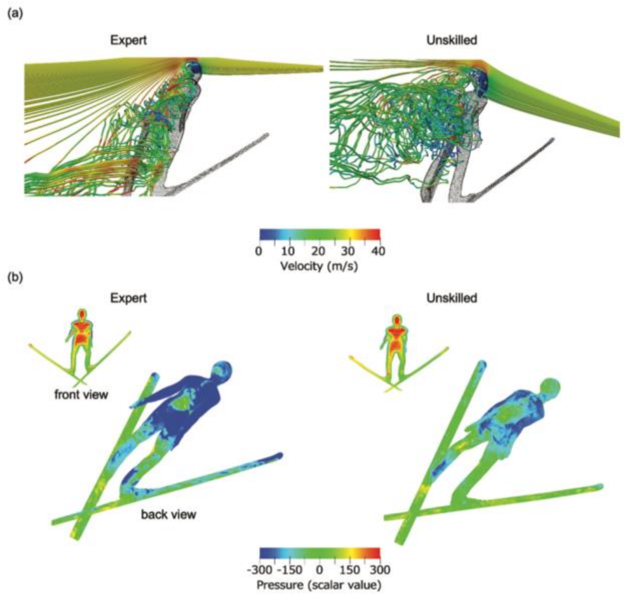


Figure 2 Framework of aerodynamic analysis of ski-jumping.

４．研究成果

The framework developed for aerodynamic analysis of ski-jump involves the four steps depicted in Figure 2.　Step 1 involves the generation of 3D shape data of the ski jumper and the skis. The digital dummy model of the ski-jumper created for an earlier study (Yamamoto et al., 2016) was adopted for the present work. The shape data of skis for ski jumping were also obtained using a 3D laser scanner . For step 2, ski jumpers are observed for the motion-capture experiment. A full-body wearable motion capture system is used to acquire the relative orientation of body segments during the actual movements of ski jumpers. To measure the orientation in space of the skis, one sensor was added to each ski. At the same time, a high- precision Global Navigation Satellite System is attached to the subject to obtain flight trajectories. The GNSS sensor is attached to the ski jumper's helmet. The direction of travel and flying speed are calculated from the flight trajectory obtained using the GNSS sensor. This information is used to ascertain the inflow direction and velocity for numerical calculations. In step 3, a three-dimensional computer graphics model is created from the surface shape data and motion data using Blender open-source 3D software. In step 4, numerical analysis is performed using the method described above.



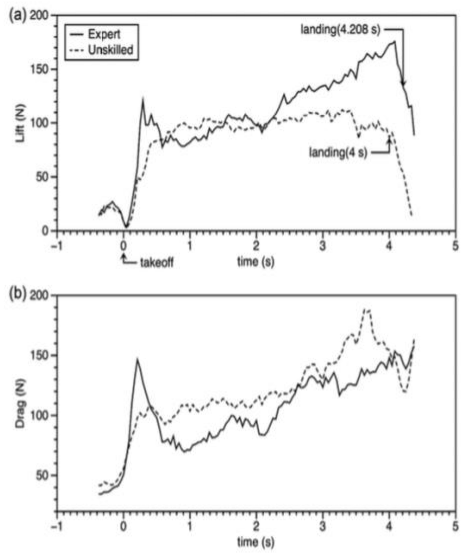


Figure 3 Left: (a) Streamline patterns coloured by speed around ski jumpers' back and (b) static pressure distribution along the surface of the ski jumpers' body at 3.5 s after takeoff. High pressures are shown in red. Low pressures are shown in blue in panel (b). The web version of this article provides interpretation of the references to colour in this figure.

Right: Time variation of aerodynamic characteristics during flight ((a) lift, (b) drag, and (c) L/D). Time zero represents the moment of takeoff. The solid line represents Ryoyu Kobayashi. The dashed line represents an unskilled jumper.

The framework developed for the study of ski-jumping was used to analyze the aerodynamic characteristics of ski jumpers during a series of movements with attitude changes. The study was conducted using two ski jumpers, one of whom was an expert jumper (Ryoyu Kobayashi) who won a gold medal in the individual normal hill at the 2022 Beijing Winter Olympics. The other jumper was an unskilled jumper. The results indicated that both the lift and drag forces of the expert jumper increased rapidly during the initial flight when the jumper's posture changed drastically. Thereafter, the drag force decreased considerably, but the decrease in the lift force was less drastic. Later in the flight phase, the lift force acting on the expert jumper increased, and throughout the flight phase, the lift-drag ratio of the expert jumper remained higher than that of the unskilled jumper. This research is valuable for understanding the aerodynamics of ski jumping and how the movements and attitudes of the ski jumper affect the aerodynamic forces acting on them. This knowledge can be used to improve the design of ski jumping equipment, training methods and overall performance of ski jumpers. The time history of the lift and drag forces is presented in Figure 3. In Figure 3, the streamlines of the flow around the ski jumper's back and pressure distribution along the ski jumper's body at 3.5 s after the takeoff are presented.

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5．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

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2．論文標題 A one-sided direct forcing immersed boundary method using moving least squares	5．発行年 2021年
3．雑誌名 Journal of Computational Physics	6．最初と最後の頁 110359～110359
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jcp.2021.110359	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Yamamoto Keizo、Nishino Takahiro、Bale Rahul、Shimada Tokimasa、Miyamoto Naoto、Tsubokura Makoto	4．巻 NA
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/14763141.2022.2154256	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

1．発表者名 Keizo Yamamoto
2．発表標題 Analysis of Aerodynamic Forces Acting on a Ski Jumper from Takeoff to Landing Using Computational Fluid Dynamics
3．学会等名 The 27th Annual Congress of the European College of Sport Science（国際学会）
4．発表年 2022年～2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

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