Short Communication : Rugby Football

Computational Analysis for Motions of Rugby Balls Interacting with Air Flows

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Computational simulations of motions of rugby balls are presented. Fluid-structure interaction plays an important role in rugby ball motion. An incompressible Navier-Stokes equation is solved on a Cartesian coordinate system. The rugby ball motions are calculated simultaneously using Newton's equation of motion for transitional motion and Euler's equation of motion for rotation. Computational results for screw and high punt kick cases are compared with those obtained from experiments.

Keywords: computational fluid dynamics, fluid-structure interaction, screw kick, high punt kick

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1. Introduction

Modern rugby strategies incorporate kicks of many kinds, which serve important roles in winning matches. They are such an important factor in rugby competition because it is difficult to break an advanced system's defensive line merely using simplified attacks involving runs and passes. Particularly, it is difficult for small Japanese teams to win against large European teams and teams from the Southern Hemisphere. Their members are typically larger than Japanese players. Because rugby football requires forceful impact of players' bodies, the strategic kick is especially valuable for teams with players of shorter builds and lesser physical ability. Teams with larger players can also use strategic kicks according to game circumstances. Concomitantly with the development of rugby football, kicks of many kinds have become increasingly important in matches. In addition to advancing a team's position, they have been used to reduce enemy pressure and to get the ball again. Furthermore, kicking accuracy has come to be regarded as an important aspect of play through introduction of Experimental Law Variations (ELV) in recent years. Especially, using the screw kick to gain distances, low accuracy can instead produce unfavorable situations. In rugby football, kicking and ball control depend on players' experience. It cannot be said that they are explainable scientifically. Nevertheless, this study simulated motions of rotating rugby balls and surrounding airflows using fluid-structure interaction analysis. Based on these results, we seek to determine optimal conditions of rugby football kicking.

2. Governing equations

For this study, two different coordinate systems are used: one is fixed to a center of gravity of the rugby ball; the other is fixed to the rugby ball surface. The latter coordinate system therefore rotates with the rugby ball. **Figure 1** portrays these two coordinate

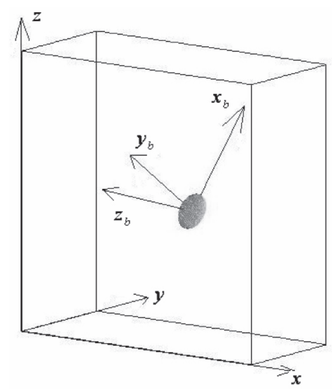

Figure 1 Coordinate systems

systems (x, y, z) and (x_b, y_b, z_b). For this study, the rugby ball shape is represented as a distribution of the characteristic function $\kappa\,(x, y, z)$, which takes a value of one in the rugby ball and zero out of it.

Air around the rugby ball is assumed to be governed by incompressible Navier-Stokes equations, as

$$\frac{\partial \boldsymbol{u}}{\partial t} + \{(\boldsymbol{u} + \boldsymbol{u}_m)\cdot\nabla\}\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\boldsymbol{u} - \frac{\partial \boldsymbol{u}_m}{\partial t} - C\kappa(\boldsymbol{u} - \boldsymbol{u}_s)$$

where $\boldsymbol{u}$, p, ρ and ν respectively represent the velocity, pressure, density, and kinematic viscosity of air. Furthermore, $\boldsymbol{u}_m$ and $\boldsymbol{u}_s$ are velocities because of transitional motion and rugby ball rotation, which are governed respectively by Newton's equation of motion

$$M\frac{d\boldsymbol{u}_m}{dt} = \sum_i \boldsymbol{F}_i$$

and Euler's equation of motion, as

$$I\frac{d\boldsymbol{\omega}}{dt} + \boldsymbol{\omega}\times I\boldsymbol{\omega} = \sum_i \boldsymbol{r}_i \times \boldsymbol{F}_{bi}$$

In those equations, $\boldsymbol{\omega}$, M, and I respectively signify the rugby ball's angular velocity, mass, and moment of inertia. Also, $\boldsymbol{F}_i$ denotes fluid dynamical forces exerting on the rugby ball by airflow, which are computed using a volume integration.

$$F_j = \int_\Omega \sigma_{jk}\cdot n_k\, d\Omega$$

The stress tensor is defined as

$$\sigma_{ij} = -p\delta_{ij} + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$

Therein, n_k is a zero extension of the outward normal vector of the boundary, as computed by the gradient of $\kappa(x, y, z)$.

The rugby ball rotations are represented by quaternion $Q=t+s_x i+s_y j+s_z k$, by which complex combination of rotations can be computed simply. Using the quaternion, the rugby ball rotation speed $\boldsymbol{u}_s$ is computed from angular velocity $\boldsymbol{\omega}$.

For details of the formulation described above, please refer to a report of an earlier study (Tanino, 2009).

3. Numerical methods

Governing equations presented in the preceding section are discretized using finite difference method.

Figure 2 Screw kick

Figure 3 High punt kick

A simplified MAC method is used for time evolution. All spatial derivatives, except for convection terms, are approximated by the second-order central differences. The convection term is approximated by the third-order upwind scheme. The Poisson equation for pressure is solved using GP-BiCG method with incomplete LU factorization as a preconditioner.

4. Experiments

Kicks of two types–A) screw kick and B) high punt kick–are performed by a player. The loci, flying distances, initial velocities, initial rotation speeds, and directions are recorded using a high-speed digital camera and a video camera. In the screw kick case, the rugby ball rotates around its long axis, whereas the ball rotates around its short axis in the high punt kick case. **Figure 2** and **Figure 3** respectively show synthesized photographs for two cases. The initial

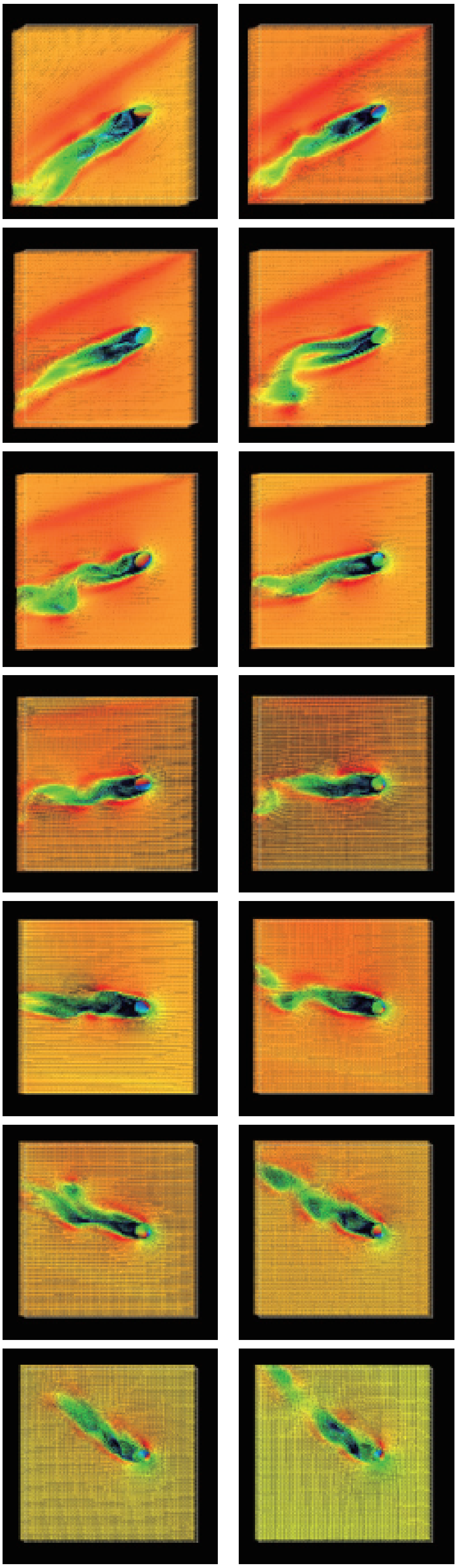

Figure 4 Screw kick simulation results

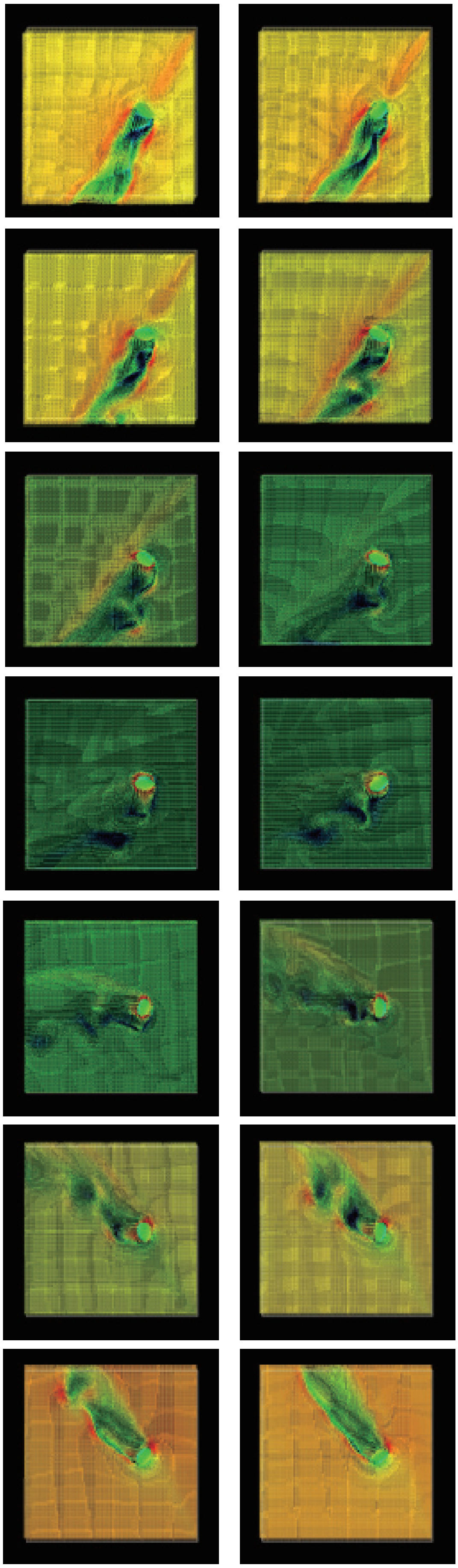

Figure 5 High punt kick simulation results

Table 1 Experimental results

	Screw kick	High punt kick
Initial velocity	25–30 m/s	20–25 m/s
Initial rotation	7–9 rps	9–11 rps
Initial angle	35–45°	50–60°
Flying distance	35–47 m	28–35 m
Transversal stray	-3.7–7.5 m	-1.1–6.3 m

Table 2 Initial conditions for simulation

	Screw kick	High punt kick
Initial velocity	28 m/s	23 m/s
Initial rotation	7.5 rps	10 rps
Initial angle	35°	60°

velocity, rotation and angle of elevation are tabulated in **Table 1** with resultant flying distances and transversal strays.

5. Computational results

Initial conditions for simulations are tabulated in **Table 2**, as selected from experimental results. **Figure 4** and **Figure 5** show computed velocity vectors around the rugby ball. Red, green, and blue respectively represent high, medium, and low flow speeds. The time sequence is left to right and top to bottom. In the screw kick case, the ball's wake is not so wide and the horizontal speed does not decrease rapidly. However, in the high punt kick case, the rugby ball rotation twists strongly in the near wake; the horizontal speed becomes almost zero at the highest position.

6. Discussion

Figure 6 and **Figure 7** respectively depict the flying heights and transversal strays obtained during the simulation. As portrayed in **Figure 7**, for the screw kick case, the flying direction in horizontal plane changes twice, as observed also in this experiment. However, in the high punt kick case, the transversal stray is almost zero. This represents an important feature of the high punt kick: its ease of landing point control. The total flying distance and transversal stray are tabulated in **Table 3**. Unfortunately, these distances are not in good agreement for experimental and simulation results. A possible reason for these discrepancies is wind, which was not considered in these analyses.

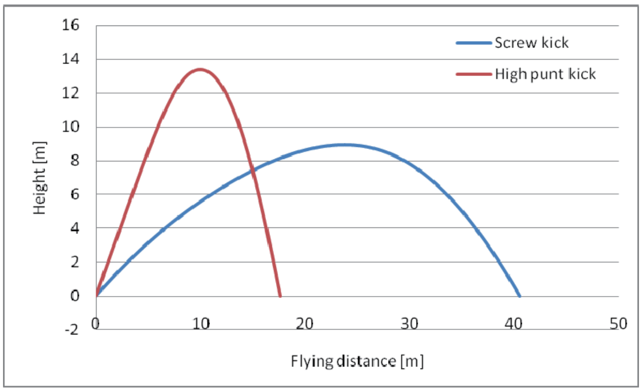

Figure 6 Simulation result for flying height

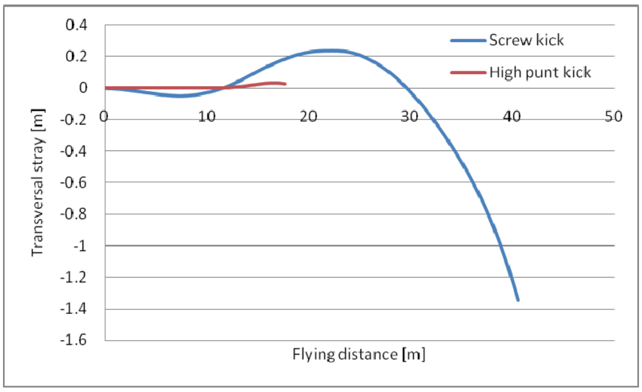

Figure 7 Simulation result for transversal stray

Table 3 Comparison of experimental and simulation results

		Experiment	Simulation
Screw kick	Flying distance	47 m	40.6 m
	Transversal stray	1.4 m	1.7 m
High punt kick	Flying distance	30 m	18.2 m
	Transversal stray	0.3 m	0.0 m

7. Conclusions

As described herein, computational simulations for motions of rugby balls with its rotations are presented. Computational simulations show good qualitative agreement with results of experiments. Although the quantitative agreement is not satisfactory, such simulations can reveal detailed aspects of rotating rugby ball motions. This and subsequent studies are expected to provide useful information for actual kick strategies and to elucidate optimal kicking conditions.

References

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