MEASUREMENT OF THE AERODYNAMIC STABILITY AND CONTROL EFFECTIVENESS OF HUMAN SKYDIVERS

[1]G. Cardona, [1]D. Evangelista, [1]N. Ray, [1]K. Tse, [1]D. Wong

[1]University of California, Berkeley, CA, USA
email: gcardona29 at gmail dot com

INTRODUCTION

In comparative biomechanics, understanding the role of maneuvers during high angle of attack flight is critical to understanding the evolution of aerial behaviors like flight. We report the aerodynamic stability and control effectiveness of human skydivers in free fall measured using physical models in a wind tunnel. The effect of posture and movements of the limbs is examined and compared to previously published simulation results and to guidance given during typical skydiving instruction, as well as the experience of human skydivers in a vertical wind tunnel and during actual free fall maneuvers. Comparison will also be made to other animals in free fall and in high angle-of-attack aerial maneuvers.

METHODS

Physical models of human skydivers (Figure 1) were constructed using six-inch artists' anatomical manikins (Dick Blick; Galesburg, IL) placed in typical human skydiving postures [1]. Aerodynamic forces (lift, drag, and side force) and moments (pitch, roll, and yaw) acting on models in a wind tunnel were measured using a six degree-of-freedom force/torque sensor (ATI Industrial Automation; Apex, NC). Forces and moments were normalized to the planform area of a "flat" resting human. To quantify static aerodynamic stability, models were placed at varying pitch, roll, and yaw angles and the restoring torques acting about the center of gravity were measured and used to obtain static stability coefficients (e.g., $dC_m/d\alpha$) [2,3,4]. Similarly, control effectiveness was measured by placing limbs in turn or roll positions (see Figure 1) and measuring the resulting yawing or rolling moments to obtain control effectiveness coefficients (e.g., $dC_m/d\delta$) [2,3,4].

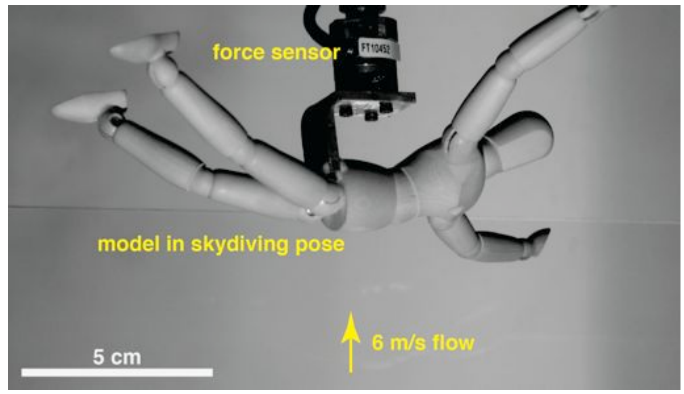

Figure 1: Physical model of a human skydiver, mounted on a force/torque transducer in a wind tunnel. Body twist creates a left yaw moment.

We compared stability and control effectiveness observed in model tests to statements in skydiving training literature [1], photo and video of stable positions openly reported on the Internet, and descriptions from interviews with professional skydiving instructors.

RESULTS AND DISCUSSION

Preliminary results from model tests agree with non-quantitative skydiver self-assessments of

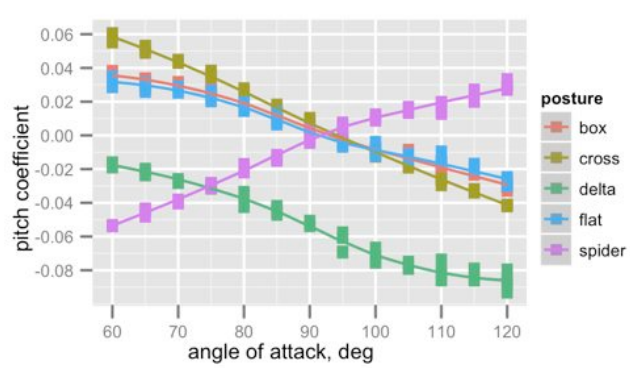

Figure 2: Nondimensional pitch coefficient (C_M) as a function of angle of attack for typical skydiving postures shows clear differences in static stability; spider position is unstable and track/delta position is only stable at lower angle of attack.

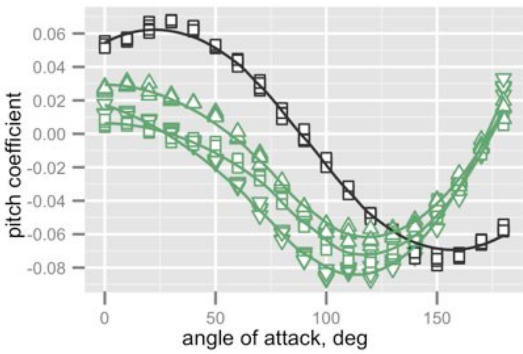

Figure 3: Nondimensional pitch coefficient (C_M) as a function of angle of attack for track/delta position as arms angle is varied 20° up and down, illustrating pitch control effectiveness.

stability and maneuverability. Different skydiving postures exhibit clear differences in stability and in stable orientation relative to flow (Figures 2 and 3).

These results suggest that skydivers maneuver principally using aerodynamic forces vice inertial reactions. At low speeds, zero angular momentum turns affected by inertia of limb movement, changes in body inertia and body position changes drive changes in body orientation (e.g., gymnastics [5], cliff diving, or other acrobatic maneuvers performed at low speed close to the ground). In contrast, at skydiving speeds (54 m/s, 120 mph), maneuvers are dominated by aerodynamic torques, which scale as ½ $\rho u^2 \lambda S$. For example, in track/delta posture, elevation of the arms has sufficient control to create a one-for-one angular pitch change of the body (Figure 3).

As a further test of the relative roles of inertial reactions versus aerodynamic forces, we are currently comparing predicted turn and roll dynamics to those observed in the absence of flow (while statically hanging from a line on the ground), and to maneuvers in a full-scale vertical wind tunnel (iFly; Union City, CA) and during actual skydives (Bay Area Skydiving; Byron, CA). Skydivers have recently adopted miniature GPS loggers originally developed for do-it-yourself unmanned aerial vehicles, and regularly use such tracks to examine their own glide performance and compete with others. Using off-the-shelf components (SparkFun; Boulder, CO), we have ground-tested loggers that record accelerations, angular velocities, and magnetometer readings at 50 Hz and GPS positions at 4 Hz (example data, Figure 4). A Kalman filter is then applied to estimate full-scale aerodynamic forces and moments during typical maneuvers, such as the turns and rolls required for entry-level skydiving licensing (US Parachuting Association A-level) [1].

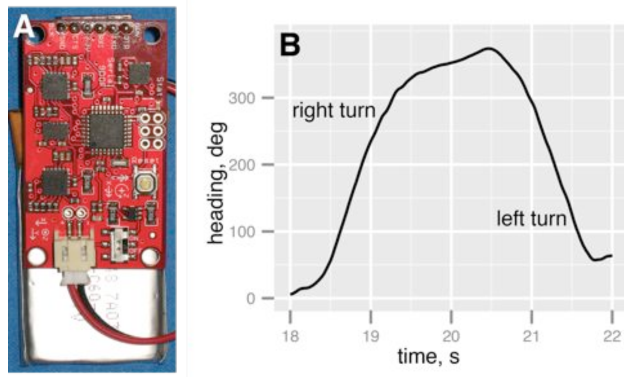

Figure 4: Wearable accelerometer (A, width 2.7 cm, mass 30 g) and integrated heading data for series of rapid 360° turns (simulated on the ground) (B).

CONCLUSIONS

Animals in free fall must maneuver into preferred stable orientations and to affect safe landings. Human free fall is an under-studied, but important, point of comparison, because humans use both inertial and aerodynamic maneuvering mechanisms (depending on speed); skydivers can be asked the rationale behind techniques and can be asked to perform specific test maneuvers; and because of the important practical applications of skydiving.

REFERENCES

1. Poynter D and Turoff M. *Parachuting: The Skydiver's Handbook*, Para Publishing, 2007.
2. McCay MG. *J exp Biol* **204**, 2817-2826, 2001.
3. Koehl M, et al. *Integ Comp Biol* in prep.
4. McCormick BW. *Aerodynamics, Aeronautics and Flight Dynamics*, John Wiley & Sons, Ltd., 1976.
5. Playter R. *Passive Dynamics in the Control of Gymnastic Maneuvers,* PhD Thesis, 1994.

ACKNOWLEDGEMENTS

We thank the Berkeley Biomechanics group, esp. Y. Zeng and Y. Munk. We dedicate our work to Alex Lowenstein, who inspired this research and whose loss helped us decide that today is a good day to skydive.