INTRODUCTION

In paralympic cross-country skiing, athletes compete in one of three categories: visually impaired athletes compete with an able-bodied guide and use 2 skis and 2 poles; standing athletes compete using 2 skis and 0, 1 or 2 poles; and sitting athletes compete on a sit-ski with 2 skis and use 2 poles. Even within each category there is a wide range of disabilities, for example, from complete impairment of the lower limbs and minimal trunk muscle activity for LW10 sitting athletes, to only partial impairment of the lower limbs and normal trunk muscle activity for LW12 sitting athletes. Actual race time is thus multiplied by a percentage factor dependent on disability and the skier with the lowest calculated race time within each category is the winner.

Furthermore, disability obviously affects the muscle power produced by the athlete to increase and maintain speed, but for sit-skiers it also uniquely affects their ability to negotiate turns. An LW12 sit-skier can lean toward the inside of a turn to increase the centripetal force and thus avoid tipping over toward the outside of a turn. However, an LW10 sit-skier is physically unable to lean into a turn and can only avoid tipping over toward the outside of a turn by using his outside pole to push himself toward the inside of a turn. Their only other option is to slow down to negotiate turns, which is not the best strategy if they want to win a race.

The completely rigid structure of current sit-ski designs makes negotiating turns especially difficult. Indeed, whether it is because they under-compensated or over-compensated for a turn, sit-skiers will often find themselves precariously balancing on only one ski during turns, narrowly avoiding tipping over toward the outside or the inside of the turn. The purpose of this project was thus to improve sit-ski design to make it more stable and more agile during turns. To do so we studied the effect of adding a tilting mechanism to the sit-ski on maximum allowable turning velocities.

METHODS

So as to better understand the biomechanics of a cross-country skier negotiating a turn on a tilting sit-ski, a simple dynamic model was elaborated (Figure 1). We then determined the effect of centre of mass (h) and center of rotation (hr) heights, turn radius (r) and lean angle of skier and sit-ski (φ) on the maximum allowable turning velocities (vmax).
RESULTS

At the limit of stability, the internal ski forces ($F_{zi}$ and $F_{yi}$) tend to zero and the cross-country skier is about to tip over toward the outside of the turn. Our model then showed that the maximum allowable turning velocity is given by:

$$v_{\text{max}} = \sqrt{\frac{r \cdot g}{\frac{t}{2} + (h - h_r)^2 \sin \phi \cos \phi}}$$

Our model results showed that:

- Maximum allowable turning velocity ($v_{\text{max}}$) increased if centre of mass height ($h$) decreased (Figure 2).
- Maximum allowable turning velocity ($v_{\text{max}}$) increased if center of rotation height ($h_r$) decreased (Figure 3).
- Maximum allowable turning velocity ($v_{\text{max}}$) increased if turn radius ($r$) increased (Figure 4).
- Maximum allowable turning velocity ($v_{\text{max}}$) increased if lean angle of skier and sit-ski ($\phi$) increased (Figures 2, 3 and 4).

DISCUSSION AND CONCLUSIONS

Therefore, to increase the maximum allowable turning velocity ($v_{\text{max}}$) a sit-ski with a tilting mechanism should have low centre of mass ($h$) and center of rotation ($h_r$) heights. This is especially important for tight turns, since the maximum allowable turning velocity ($v_{\text{max}}$) decreases if turn radius ($r$) decreases (Figure 4).

A tilting sit-ski design would thus allow both skis to remain in contact with the ground when negotiating turns and could allow even LW10 athletes to lean toward the inside of a turn to go faster. In fact, for the tightest turns ($r=15m$), a lean angle of skier and sit-skier ($\phi$) of only 5 to 10deg could increase maximum allowable turning velocity ($v_{\text{max}}$) by 0.68 to 1.31m/s (Figure 4).

These results were experimentally validated in the field and, to date, have resulted in one silver and one bronze medal at the 2010 Paralympic Games in Vancouver.

ACKNOWLEDGEMENTS

This work was funded by the Own the Podium – Top Secret 2010 program from the Canadian Olympic Committee. We also thank the Canadian paralympic cross-country ski team.

**Figure 2:** Maximum allowable turning velocity ($v_{\text{max}}$) as a function of center of mass height ($h$) and lean angle of skier and sit-skier ($\phi$) with $r=15m$, $g=9.81m/s^2$, $t=0.23m$, $h=0.569m$.

**Figure 3:** Maximum allowable turning velocity ($v_{\text{max}}$) as a function of center of rotation height ($h_r$) and lean angle of skier and sit-skier ($\phi$) with $r=15m$, $g=9.81m/s^2$, $t=0.23m$, $h=0.569m$.

**Figure 4:** Maximum allowable turning velocity ($v_{\text{max}}$) as a function of turn radius ($r$) and lean angle of skier and sit-skier ($\phi$) with $g=9.81m/s^2$, $t=0.23m$, $h=0.569m$, $h_r=0.222m$. 