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A Fundamental Study on the Aerodynamics of Four Middle and Long Distance Running Shoes

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Abstract. The primary objective of this study was to examine the aerodynamic properties of a selection of four middle and long distance running shoes. Four pairs of running shoes were tested on a specially constructed rig which was inserted into a fully calibrated wind tunnel. The running shoes where angled at incidences of 90^0, 50^0 plantar flexion and 10^0 dorsi flexion to the direction of the air flow. The wind tests included average speeds around 3, 4, 5 and 6m/s. There was variation in the drag coefficients between the various shoes with one shoe in particular demonstrating the lower drag across all but one of the tests undertaken. The optimum speed for the least drag in the shoes tested was shown to be around 5m/s. The aerodynamics properties of running shoes may be important to consider in future shoe design: particularly where long running distances are being undertaken and where weather conditions are unfavourable. Further work in this area is justified if optimal long distance running shoe design is desirable.

Keywords: Running shoes; aerodynamics; wind tunnel

1. Introduction

Whilst there are recent advances in shoe design with a focus on materials, little attention has been given to the aerodynamics of the shoe both in terms of upper shoe design and the overall composition of the frontal aspects of the shoes.

The importance of aerodynamics in selected sports is well documented. There is a plethora of literature from selected sports on the aerodynamics of the sporting equipment used, particularly on the materials used to enhance athletes' performance in terms of skill, speed, balance and other attributes associated with a given sporting performance.(Riley and Lees,1984; Kyle, 1994; Wu and Gervais, 2008: Barber *et al.* 2009). A contemporary example in terms of equipment is the laboratory designed World Cup football, used for the World Cup finals in South Africa in 2010. This football was specially textured with grooves which were intended to improve the ball's aerodynamics and decrease "wobble". (Ghosh, 2010). Footballs used in World Cup tournaments are specially commissioned for each competition, and use the most advanced technology to enhance the football design, in terms of aesthetics and performance. The manufactures Adidas suggested that the textured design would help goal keepers handle the ball and would help the flight of the ball, in a similar way to the dimples on a golf ball. A similar example but in a different sport was the development of Speedo Fastskin FSII swimsuit in 2004. This swimsuit was developed by computational fluid dynamic modelling, and demonstrated through extensive testing, a reduction of passive drag by up to 4% on their swimsuit compared to the next best suit (ANSYS, http://www.fluent.com/about/news/newsletters/04v13i1/a1.htm).

Companies and indeed athletes' are always looking for something that will give an extra edge in terms of performance allowing them to move faster, slide smoother or facilitate more distance. The advance in all aspects of sports science has indeed allowed athletics to achieve records that were unthinkable a few decades ago. However with this strive for faster and better designed equipment; sporting governing bodies have had to give serious thought as to how best to regulate equipment design for their particular sport. Regulatory requirements in terms of design are now an integral part of most sports and aerodynamic enhancement is an important consideration in certain sports.

In relation to lower limb, the application of aerodynamic testing in terms of sporting kit and design materials is poorly documented. There is a paucity of work in this area specifically around the foot and ankle. One of the first studies to look at aerodynamics in this area was worked carried out by Asai *et al* in 2004. These authors undertook an analysis of the aerodynamics of athletic spike shoes and examined the effects of the aerodynamics of spiked shoes comparing wind tunnel tests with CPD analysis. Ashford *et al* in 2009 suggested that the orientation of the foot in a middle/long distance running shoe has an important effect on the drag and may subsequently have an effect on the energy consumption of long distance runners over a prolonged period of time.

During running the foot has a 3D trajectory in space. The complexity of foot and leg movement during gait and running is well documented and normal ranges of motion have been captured (Mann and Hagy, 1980; Areblad *et al*, 1990;Hagel *et al.* 1993; Mitchell *et al* 2008). However, this normative data doesn't take account of individual foot pathologies with some individuals exhibiting excessive in-toeing or indeed abductory twisting of the foot during the swing phase of the gait cycle. Whilst a previous study reported in the association between the foot structure and the development of musculoskeletal overuse injuries (Kaufman, 1999), .there is a clear paucity of information on pathological and non pathological deviation from normative kinematics. One only has to look at the kinematics of foot movement during any running activity to appreciate the variation in the population at large. It can therefore be argued that variations outside the normative foot positions during the swing phase of the gait cycle are potentially going to increase the drag on the shoe, which in turn may have an effect on the total energy consumption over time. As in flight dynamics a plane also has the possibility of moving around in a three dimensional axis: these movements are called the Pitch, Roll and Yaw. In this preliminary study we were particularly interested in the Pitch and Yaw because these movements will increase the surface area being exposed to the air flow. The Yaw is also the one most prominent during the swing phase of gait particularly with individuals who exhibit foot pathologies. This paper however does not report on the Yaw but focuses on the Pitch of the shoe. The Yaw data is to be reported in a follow-up paper.

This pilot work aimed to compare and test four differently designed running shoes in a wind tunnel setting at four different wind speeds representative of running speeds including 3, 4, 5 and 6m/s, modelling foot positions in a sagital plane at “maximal” dorsal and plantar flexion.

2. Methods

A study protocol was devised; this sought to model selected positions of the foot during a swing phase of running. The protocol utilized a mannequin's foot which was inserted into the left shoe of four different size 6 UK, sports shoes including Nike Zoom; Nike Free: Nike 100km; Reebok DMXRIDE (figure 1).

Fig. 1 Shoes tested Nike Zoom; Nike Free; Nile 100km; Reebox DMX

The foot was mounted onto a purpose built rig in one of three machined cylindrical metal sockets (figure 2). These sockets had three different angle settings to allow the shoe to adopt a 90 degree, a 50 degree plantar and a 10 degree dorsal flexed position (figure 3). The rig was also able to rotate in the transverse plane and was tested at angles of -6°, -10° (adductory position) and 19° (abductory position). The projected area and length of the each of the shoes both in plan and frontal view at each orientation was recorded using a light and shadow method to later calculate drag coefficients.

Fig.2 Rig with sockets

Fig. 3 Angled sockets

The rig was inserted into a wind tunnel (figure 4) with the each of the four different sports shoe (figure 5, shows one shoe in the wind tunnel mounted on rig at 90^0) and the Reebok DMXRIDE was also placed into a smoke tunnel once the wind tunnel data had been collected (figure 6). The wind tunnel is regularly calibrated to ensure correct measurement of data. During each orientation angle, the base plate (load cell that the rig is attached to) was zero-balanced to take away any effects of the weight of the rig and shoe. The drag effects of the rig were also considered and dealt with using a tare test in which the drag of the supporting rig is determined over the range of test speeds for subtraction from the combined support and sock drag results obtained during testing. The air temperature, barometric pressure and tunnel velocity were monitored throughout all of the test runs.

Fig.4 Set up for wind tunnel

Fig. 5 Shoe in wind tunnel at 90^0 to direction of wind

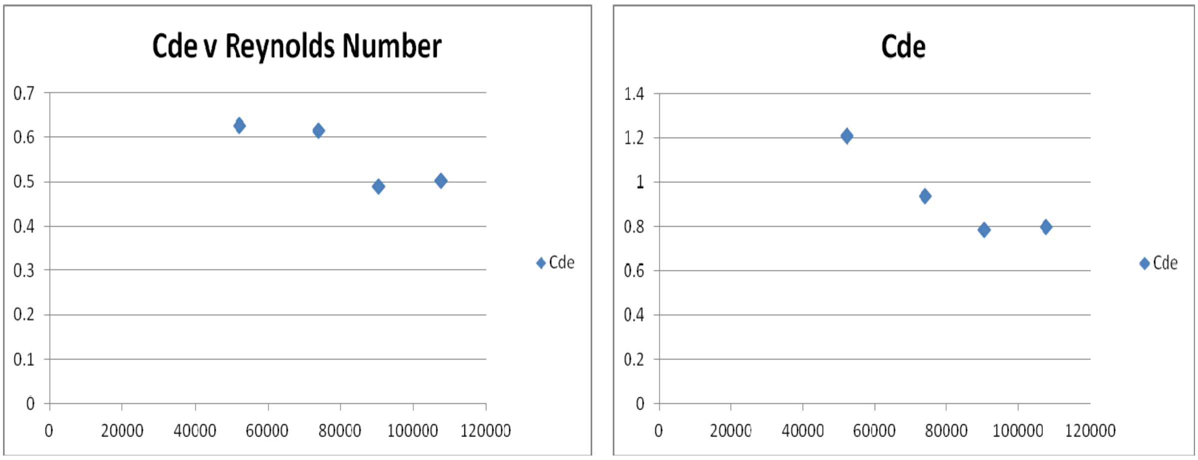
Fig. 6 Shoes at 10^0 and 50^0 in smoke tunnel

A selection of wind speeds were used including: 3, 4, 5 and 6 m/sec. A value for drag force amongst other outputs was recorded for each wind speed in each of the orientations mentioned previously.

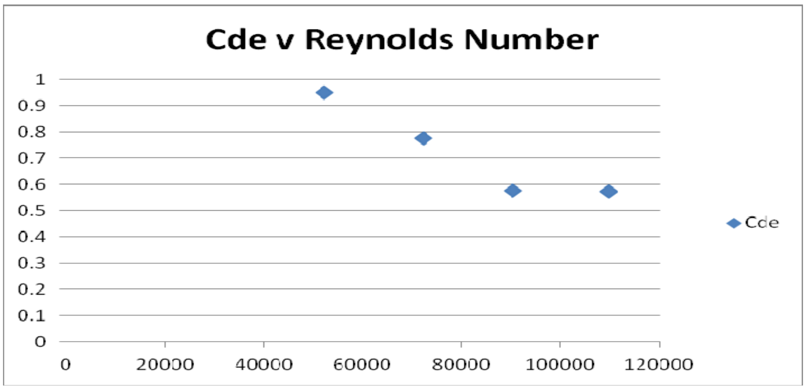
3. Results

In Table 1, the results for the four running shoes are presented at the various degrees of incidence of 90, 50 and 10. The four velocities executed for the various degrees of incidence are given and the drag coefficients (Cde) recorded for each. The coefficients are expressed in terms of their projected frontal areas. Also reported in this table are the associated Reynolds Numbers (Rel).

Figures 7-10 offer the drag coefficients and the calculated Reynolds Numbers.

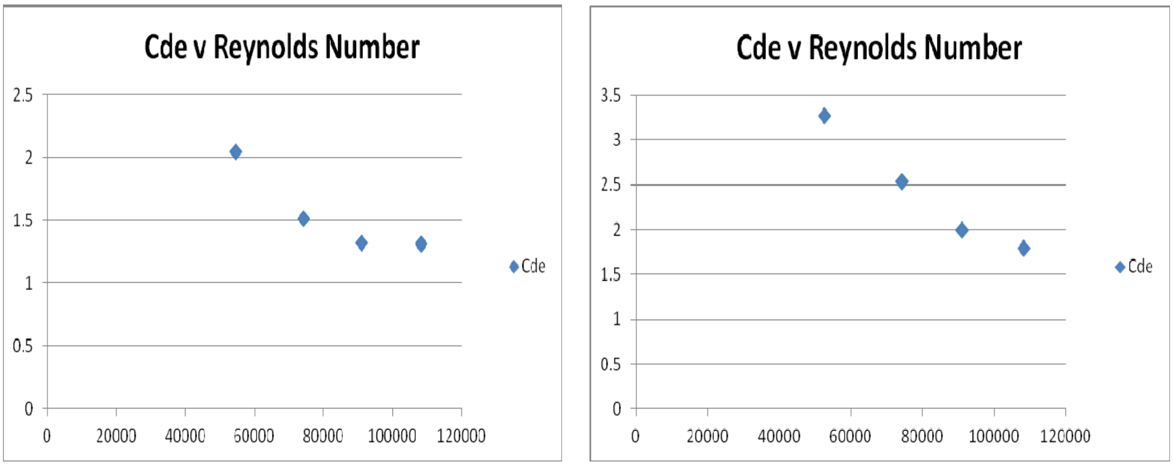


INCIDENCE 90 degrees INCIDENCE 50 degrees

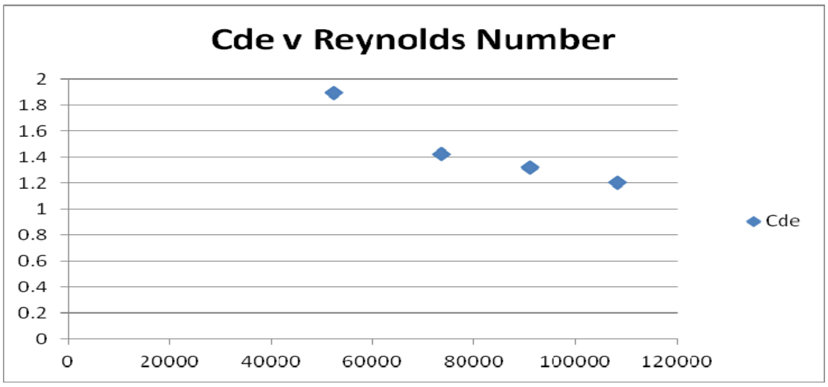


INCIDENCE 10 degrees

Figure 7 Reebok shoe at 90^0, 50^0 and 10^0 incidence

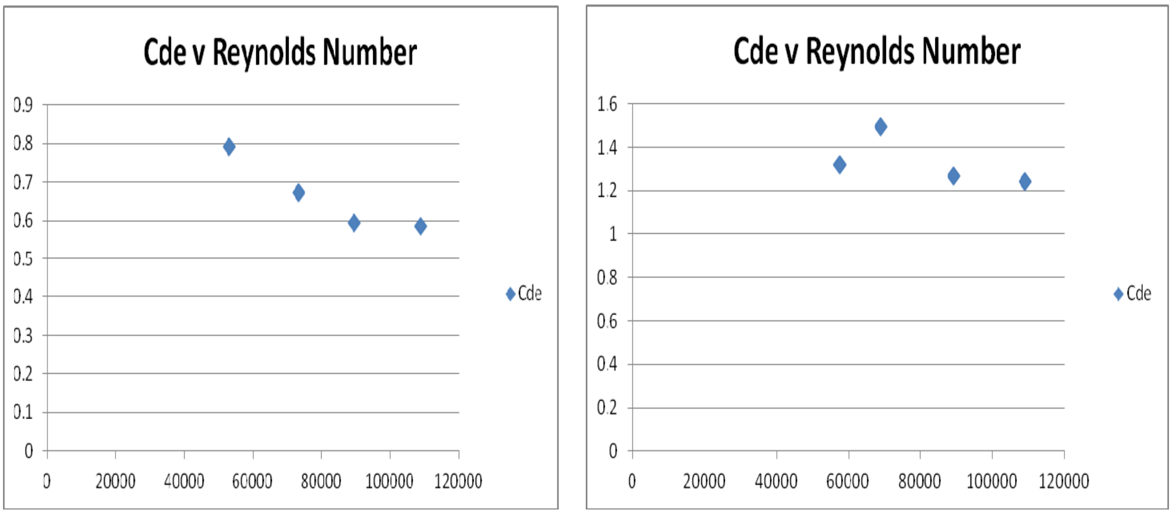


INCIDENCE 90 degrees INCIDENCE 50 degrees

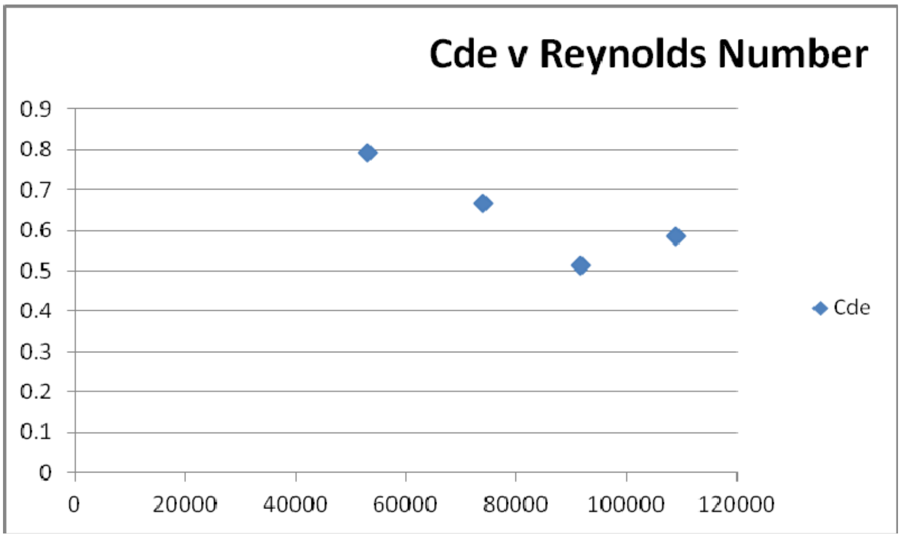


INCIDENCE 10 degrees

Figure 8 Nike 100k shoe at 90^0, 50^0 and 10^0 incidence

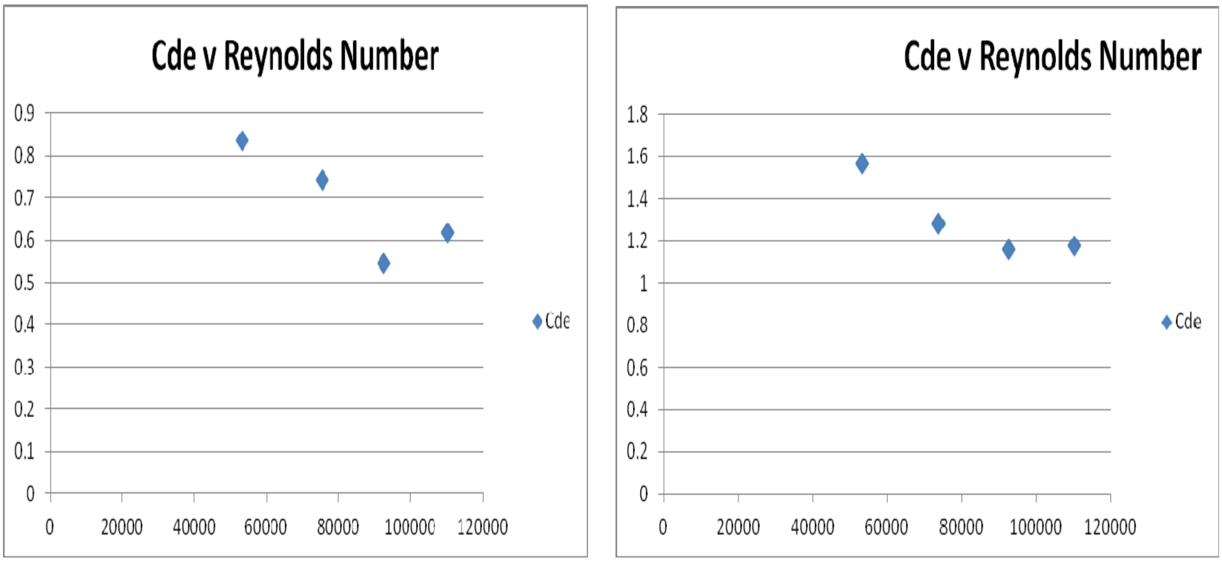


INCIDENCE 90 degrees INCIDENCE 50 degrees

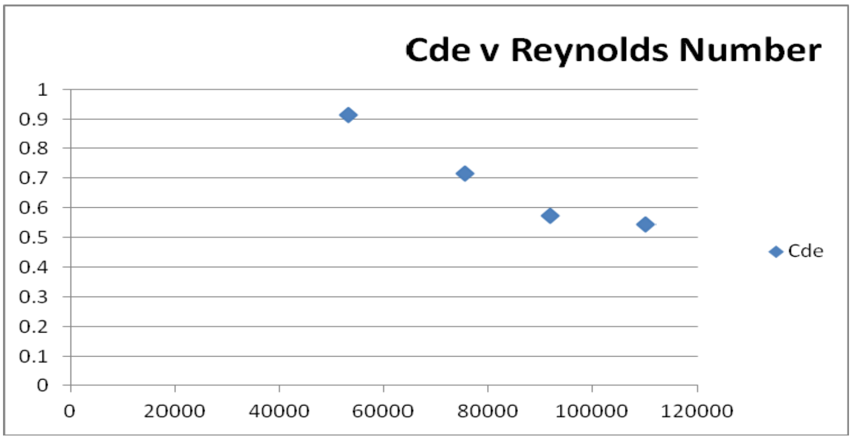


INCIDENCE 10 degrees

Figure 9 Nike Zoom shoe at 90^0, 50^0 and 10^0 incidence



INCIDENCE 90 degrees INCIDENCE 50 degrees



INCIDENCE 10 degrees

Figure 10 Nike Free shoe at 90^0, 50^0 and 10^0 incidence

4. Discussion and Conclusion

This work follows an initial pilot study by Ashford *et al* (2009) where the authors concluded that the orientation of the foot during the swing phase of gait may be affected unduly by drag, particularly if the swing is atypical and is over a long period of time. They suggested that the Yaw may have an effect on energy consumption and therefore recommended further work was needed to confirm this. The work reported in the current paper has not reported on the Yaw question, but has shown that the drag on different running shoes varies, and that the trend of drag coefficient decrease with increase in Reynolds Number is consistent with results obtained for bluff bodies. A curve of this type is shown in Figure 11. The essence of this curve demonstrates that at the bottom of the curve the recorded air speed gives the minimal drag. This is consistent with our results figures 7-10 where the reduction in the coefficient of drag can be detected in each of the graphs which results in optimum speed to achieve minimal drag in the shoes tested is around 5m/s. figure 11 shows that there are two regions associated with the reduction in drag coefficient. At the lower Reynolds number the reduction is associated with the viscous effects of the air, whilst at higher Reynolds Number the rapid decrease corresponds to the transition to a turbulent boundary layer and the attaining of the Critical Reynolds Number. Whist direct comparison of Figures 7-10, with Figure 11 is difficult as the Reynolds Number for the shoes is calculated using the length of the shoe, it is necessary to carry out further tests over the range of Reynolds Number portrayed in Figure 11 to ascertain whether it is viscous or boundary layer transition effects which lead to the reduction in drag coefficient

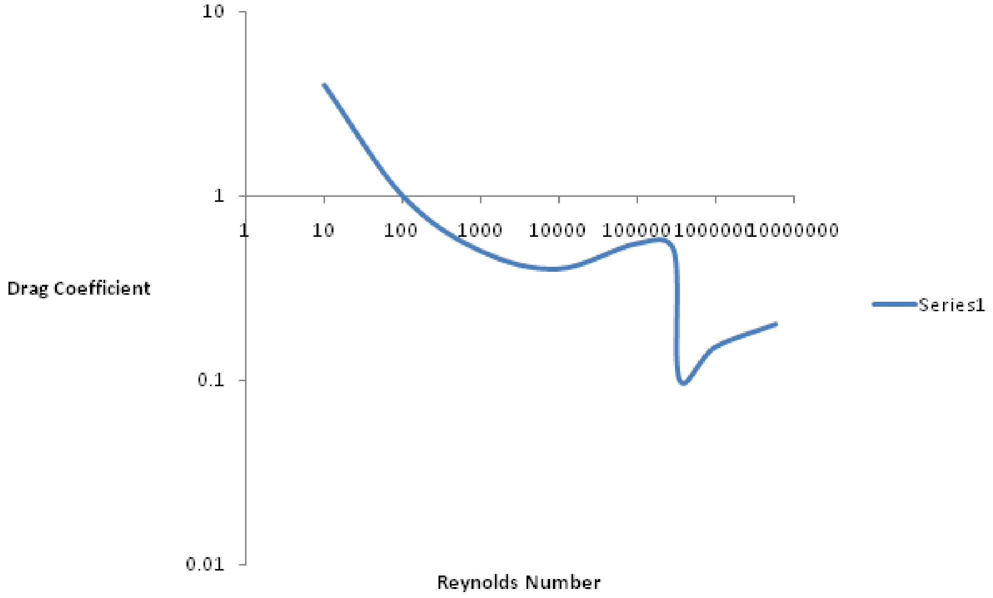


Fig. 11 3D body Drag Coefficient v Reynolds number

The shoe which shows the least drag across almost all of the data is the Reebok. The coefficients in all but one case were lower for this shoe compared to the others. One could speculate and argue that if indeed aerodynamics is found to be important in a long distance race, and if the athlete is biomechanically compromised, in terms of their swing pattern, total running shoe design may prove to be important in energy consumption and ultimately the finishing time for such an individual.

The data for Yaw is not presented in this paper but will undoubtedly have an impact on the results. It is acknowledged in this context that the data presented is modelled on a shoe that's been presented in only three orientations all of which are directly oriented towards the wind flow. The selection of 90^0, 50^0 plantar flexion and 10^0 dorsi flexion in the sagital plane is acknowledged as a limitation of the study. It would have been unwieldy at this stage of the work to try and capture the minima in the various orientations necessary to simulate a full swing phase; however this is recommended for future work.

5. References

[1] T. Reilly, A. Lees. *Exercise and sports equipment: Some ergonomics aspects Applied Ergonomics.* 1984, **15**(4): 259-279.

[2] C. R. Kyle. Energy and aerodynamics in bicycling. *Clin Sports Med.* 1994, **13**(1): 39-73.

[3] T. Wu, P. Gervais. An examination of slo-pitch pitching trajectories. *Sports Biomech.* 2008, **7** (1):88-99.

[4] S. Barber, S.B. Chin, M.J. Carré, Sports ball aerodynamics: A numerical study of the erratic motion of soccer balls. *Computers & Fluids*. 2009, **38**(6): 1091-1100.

[5] Ghosh, Pallab accessed 21/01/11 http://www.bbc.co.uk/news/10231975

[6] ANSYS, accessed 22/1210 (http://www.fluent.com/about/news/newsletters/04v13i1/a1.htm).

[7] T. Asai, K. Seo, T. Oda, T. Orei. Fundamental Study on Aerodynamics of Athletic Spike Shoes. 7th Symposium on Footwear Biomechanics, Cleveleand Ohio 2005 Abstract retrieved from Jhttp://www.staffs.ac.uk/isb-fw/cleveland_abstracts.htm

[8] R. L. Ashford, N. Shanshiri, N. Chockalingam , P. White, H. Branthwaite. A pilot study on the aerodynamics of a middle/long distance running shoe: Implications for variation in swing patterns during the running gait cycle. *Footwear Science*. 2009, **1**(S1): 20-23.

[9] R, A. Mann, J. Hagy. Biomechanics of walking, running, and sprinting. *Am J Sports Med*. 1980, **8**(5): 345-350.

[10] M. Areblad, B.M Nigg., J. Ekstrand, K.O Olsson, H. Ekström,. Three-dimensional measurement of rearfoot motion during running. *Journal of Biomechanics*. 2009, **23**(9):933-940.

[11] B.E. Hagel, E.L. Pleog, P.A. Estabrooks, J.R. Engsberg. Range of motion of the ankle joint complex in normal and overpronating runners. *Journal of Biomechanics*. 1993, **26**(I3): 316.

[12] B. Mitchell, E.Bressela, P. J.McNair, E. Bressel. Effect of pelvic, hip, and knee position on ankle joint range of motion. *Physical Therapy in Sport*. 9, 4, 202-208.

[13] K. R. Kaufman , S.K. Brodine, R.A. Shaffer, C.W. Johnson. The Effect of Foot Structure and Range of Motion on Musculoskeletal Overuse Injuries. *Am J Sports.* 1999, **27**(5): 585-593.

Table 1 Data from the four running shoes: velocity m/s; drag coefficients (Cde); Reynolds Numbers (Rel)

	Reebok			**Nike 100k**			**Nike Zoom**		**Nike Free**		
	Velocity(m/s)	Cde	Rel	Velocity(m/s)	Cde	Rel	Velocity(m/s)	Cde	Velocity(m/s)	Cde	Rel
Incidence 90^0	2.91	0.626978102	52224.28	3.03	2.045985054	54572.76	2.92	0.790889252	2.91	0.835667365	52967.22
	4.12	0.614781481	73939.52	4.12	1.514303858	74204.54	4.04	0.673769201	4.12	0.742591315	73283.42
	5.04	0.490103939	90450.29	5.05	1.318045108	90954.59	4.94	0.595171542	5.05	0.546295012	89608.93
	6	0.503469362	107678.9	6.01	1.313791375	108245	6.01	0.585934733	6.01	0.618360688	109018.2
Incidence 50^0	2.91	1.210716335	52224.28	2.92	3.275569829	52591.57	3.17	1.321476562	2.91	1.56687631	57502.09
	4.12	0.938350681	73939.52	4.12	2.533546839	74204.54	3.8	1.494390718	4.03	1.279932902	68929.95
	5.04	0.785607784	9045029	5.05	1.996450679	90954.59	4.92	1.268614074	5.05	1.161960819	89246.14
	6	0.79843121	107678.9	6.01	1.792777813	108245	6.02	1.242409509	6.01	1.175497546	109199.5
Incidence 10^0	2.91	0.951277121	52224.28	2.91	1.897149258	52411.46	2.92	0.790889252	2.19	0.914011181	52967.22
	4.03	0.77782044	72324.34	4.08	1.425361514	73484.11	4.08	0.666855091	4.12	0.716535479	74008.99
	5.04	0.576592869	90450.29	5.05	1.318045108	90954.91	5.05	0.512573098	5.01	0.572673843	91604.27
	6.12	0.571904311	109832.5	6.01	1.20430876	109235	6.01	0.585934733	6.01	0.544892091	109018.2