A2 MECHANICAL DESCRIPTORS OF LINEAR MOTION

Key Notes

Biomechanics	Is the study of forces and the effects of these forces on living things.
Kinematics and kinetics	These are subdivisions of mechanics that are concerned with displacement, velocity and acceleration (kinematics) and forces that cause or result from motion (kinetics).
Linear and angular motion	Linear motion (or translatory motion) is concerned with movement along a line that is either straight or curved and where there is no rotation and all body parts move in the same direction at the same speed. Angular motion involves movement around an axis of rotation.
Scalar quantity	A quantity that is represented by magnitude (size) only.
Vector quantity	A quantity that is represented by both magnitude and direction.
Distance and displacement	The term distance is classified as a scalar quantity and is expressed with reference to magnitude only (i.e., 14 miles). Displacement is the vector quantity and is expressed with both magnitude and direction (i.e., 14 miles north-east).
Speed and velocity	Speed is the scalar quantity that is used to describe the motion of an object. It is calculated as distance divided by time taken. Velocity is the vector quantity and it is used to also describe the motion of an object. It is calculated as displacement divided by time taken.
Acceleration	Is defined as the change in velocity per unit of time. It is calculated as velocity divided by time taken.
Average and instantaneous	Average is the usual term for the arithmetic mean. The sample mean is derived by summing all the known observed values and dividing by their number (i.e., how many of them there are). For example over a 26 mile race the average speed of the athlete was 14 miles per hour (mph). Instantaneous refers to smaller increments of time in which the velocity or acceleration calculations are made. The smaller the increments of time between successive data points the more the value tends towards an instantaneous value.

Biomechanics

Biomechanics is broadly de ned as the study of forces and their affects on living things. In mechanics there is use of a further subdivision into what is known as **kinematic** and **kinetic** quantities. Biomechanics and mechanics are used to study human motion. This section is concerned with linear (i.e., translational – where all the points move in the same direction in the same time and without rotation) kinematics. *Fig. A2.1* helps to illustrate the de nition of biomechanics and kinematics in more detail.

Human movement or motion can be classi ed as either **linear or angular motion**. Most movements within biomechanics are a combination of translation and rotation. This leads to a description that is termed **general motion**. Linear motion (or translation) is movement along a line which may be either straight or curved and where all the body parts are moving in the same direction at the same speed. This can be classi ed as either rectilinear motion (motion in a straight line) or curvilinear motion (motion in a curved line). Angular motion (which will be discussed in the next section) involves movement around an axis (either imaginary or real) with all the body parts (or individual body parts) moving through the same angle at the same time. *Fig. A2.2* identi es these types of motion in more detail.

Kinematics and kinetics

Linear kinematics is concerned with the quantities that describe the motion of bodies such as **distance**, **displacement**, **speed**, **velocity**, and **acceleration**. These

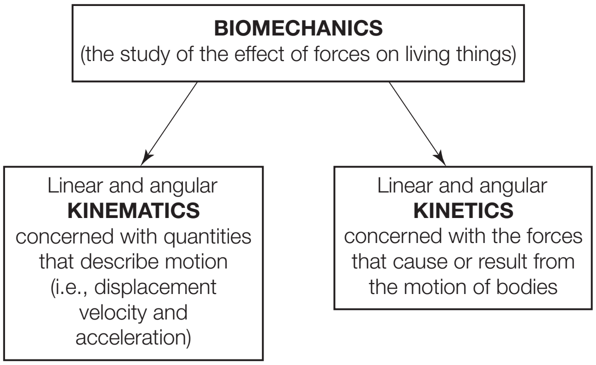

Fig. A2.1. Biomechanics, kinematics and kinetics

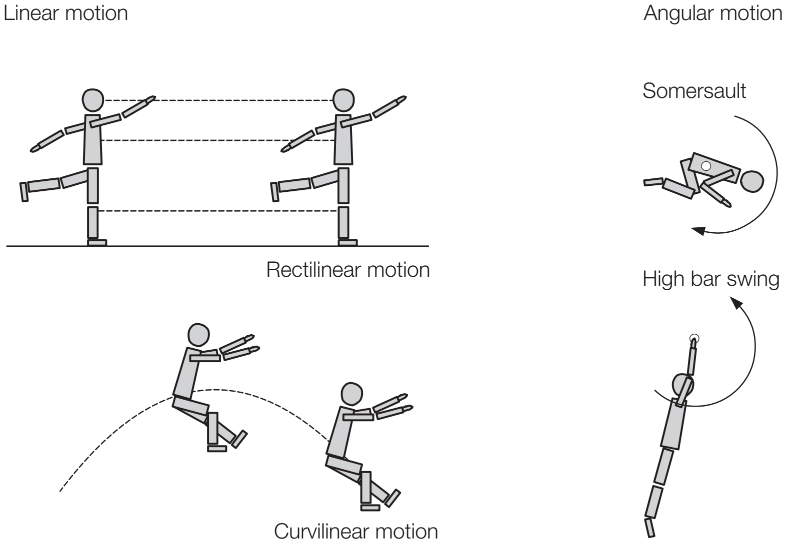

Fig. A2.2. Different types of motion

quantities can be classified as either scalar or vector quantities. **Scalar quantities** are represented by magnitude (size) only, whereas **vector quantities** are represented by both magnitude and direction. Hence, vector quantities can be presented mathematically or graphically on paper by scaled straight lines or arrows. For example, **speed** is defined as the **distance traveled** per unit of **time** and as such it is a scalar quantity (i.e., no direction is specified).

$$\text{Speed} = \frac{\text{Distance traveled}}{\text{Time taken}}$$

Ex 1. If an athlete ran 14 miles in 1 hour and 15 minutes what was the athlete's average speed?

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

$$= \frac{14 \text{ miles}}{1 \text{ hour } 15 \text{ minutes}}$$

Convert the time component to one common quantity (i.e., hours)

$$= \frac{14 \text{ miles}}{1.25 \text{ hours}}$$

$$= 11.2 \text{ miles per hour (mph)}$$

This would represent the average speed of this athlete over the whole 14 mile running activity. Hence the measure of speed in this case is a scalar quantity and is expressed in magnitude only (i.e., 11.2 mph). In this example we could have expressed speed in many different units, for example meters/second (m/s) or kilometers per hour (kph). **See if you can convert an average speed value of 11.2 mph into units of metres/second (m/s)?** ***Figs A2.3*** **and** ***A2.4*** **show the solution to this problem which present both the direct conversion of 11.2 mph to m/s and the revised calculation in m/s for the athlete described in this example.**

Scalar and vector quantities

In example 1 we can see that the athlete covered a distance of 14 miles but we do not know whether this was in a straight line, in a series of curves, or indeed in a circle starting and finishing at the same point. In this context the term speed is

1 mile = 1609.344 meters
1 hour = 60 minutes = 60 × 60 seconds = 3600 seconds

11.2 miles = 11.2 × 1609.344 m = 18024.652 m

$$\text{Speed in m/s} = \frac{18024.652 \text{ m}}{3600 \text{ s}}$$

Speed = 5.0068 m/s

Average speed of 11.2 mph = 5.0 m/s (to 1 decimal place)

Fig. A2.3. Converting an average speed of 11.2 mph into the units of m/s

1 mile = 1609.344 meters
1 hour = 60 minutes   1 minute = 60 seconds

14 miles = 14   1609.344 m = 22 530.76 m

1.25 hours = 1.25 × 60 min × 60 s = 4500 s

$$\text{Average speed in m/s} = \frac{22\,530.76\ \text{m}}{4500\ \text{s}}$$

Average speed = 5.0068 m/s

Average speed of athlete = 5.0 m/s (to 1 decimal place)

Fig. A2.4. Calculation in m/s for athlete described

used because there is no directional component speci ed. However, if we now reword this example it is possible to express the solution as a **vector quantity** such as **velocity**. Vector quantities are expressed with reference to both magnitude and direction and in the case of the runner in example 1 this can be restated as follows.

Ex 2 If an athlete covered a displacement of 14 miles in a straight line in a north-east direction in a time of 1 hour 15 minutes, what would be the athlete's average velocity over this time period?

Distance and displacement

Note: in this example the term **distance** has been replaced with the term **displacement**, which is used to express a directional component (i.e., straight line north-east direction). Although the result would be of the same magnitude (because the athlete covered the same distance/displacement in the same time) the quantity would be a vector quantity because there would now be a directional component to the solution. This vector quantity could now be expressed graphically to scale by an arrow on a piece of paper or by mathematical representation. *Fig. A2.5* illustrates this in more detail.

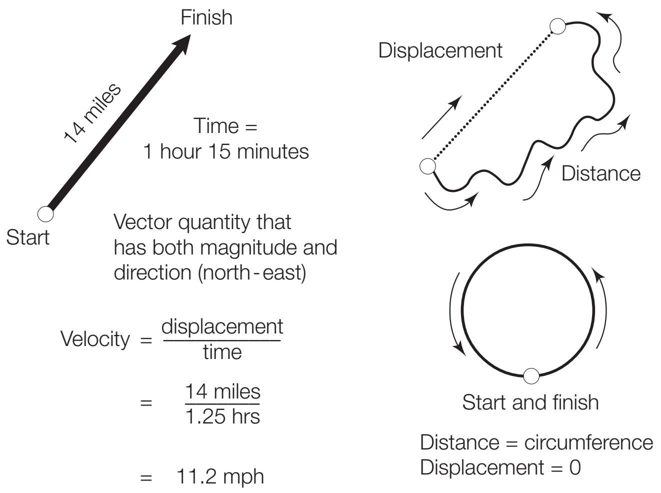

Fig. A2.5. Defining the terms distance and displacement

Speed and velocity

Often within biomechanics it is useful to be able to express both **speed** and **velocity** components. Sometimes it is only the average speed that is of interest (such as, for example, when an athlete runs a marathon race (26.2 miles or 26 miles 385 yards) and the coach is interested in getting a quick and simple measure of how the race was performed overall). As this **average speed** would be presented over a 26 mile running distance it does not really describe the speci c details of the race but it may be useful for training. Similarly, during the long jump take-off phase it is interesting to be able to know exactly what the vertical and horizontal velocities are at the point of take-off. Such information would allow the coach or scientist to be able to work out the angle of take-off and observe whether the athlete jumped with a at, long trajectory or a high, shorter one. Both these aspects (speed and velocity) are equally important for the understanding of sport, exercise, and general human movement.

Both **speed** and **velocity** can be uniform or non-uniform quantities. **Uniform** describes motion that is constant over a period of time (i.e., constant velocity or speed (no acceleration or deceleration)) and **non-uniform** describes varying or changing velocity or speed over time (i.e., with some acceleration or deceleration). In human motion it is usually the knowledge of non-uniform motion that is more bene cial to the athlete, coach, scientist, and student of biomechanics. For example, in the case of our runner in example 1, who covered 14 miles in 1 hour 15 minutes, it would be more bene cial to know what changes in the runner's speed or velocity occurred throughout the activity. Such information would have important training and performance implications and would be as valuable in a sprint race lasting no more than 10 seconds (i.e., 100 m sprint) as it would be in a marathon event lasting several hours.

Linear velocity and **acceleration** are important quantities within biomechanics that are used to describe and analyse the motion of human bodies. *Fig. A2.6* illustrates a series of 100 m sprint data from a university level athlete.

From consideration of *Fig. A2.6* it is possible to see that the athlete covered the 100 m displacement (horizontal displacement in a straight line along a track) and that this 100 m displacement is divided into 10 m sections or intervals. For example, the rst 10 m was covered in 1.66 seconds and the second 10 m in 1.18 seconds (or 20 m in 2.84 seconds (cumulative time)). It is possible to see from this

Disp. (m)	Cumulative time (s)	Time (s)	Average velocity (m/s) 10 m intervals
10	1.66	1.66	6.03
20	2.84	1.18	8.47
30	3.88	1.04	9.62
40	5.00	1.12	8.92
50	5.95	0.95	10.50
60	6.97	1.02	9.80
70	7.93	0.96	10.40
80	8.97	1.04	9.62
90	10.07	1.10	9.09
100	11.09	1.02	9.30

Average horizontal velocity over 100 m = 100/11.09 = 9.01 m/s

Fig. A2.6. Sprint data for university level 100 m athlete data that the athlete covered the whole 100 m displacement in 11.09 seconds. We can now use this data to determine **average velocity** over smaller increments (such as every 10 m interval). Such information would provide us with a biomechanical description of the whole 100 m event. The presentation and analysis of this velocity can be seen from the consideration of the calculations and data identi ed in *Figs A2.7*, *A2.8* and *A2.9*. Note: it is important to point out that this is expressed as velocity (a vector quantity) because we have a directional component (i.e., horizontal displacement along a straight 100 m track) and even though we are considering the velocity (average) over much smaller increments (i.e., 10 m intervals) it is still an average velocity over that horizontal displacement interval or section. In this context taking even smaller time intervals will eventually lead to an "**instantaneous**" value for the calculation of speed or velocity. Such analysis provides a more detailed biomechanical breakdown of the event of the 100 m sprint race.

This data (average velocity of the whole 100 m, speci c velocity for each 10 m section of the race or "instantaneous" values for even smaller time or displacement intervals) could be compared with values for Olympic and World athletic performances or indeed to other athletes within the club or university. Obviously

Average velocity over first 10 m

$$0\text{–}10 \text{ m} = \frac{10 \text{ m}}{1.66 \text{ s}} = 6.03 \text{ m/s}$$

Average velocity between 10–20 m

$$10\text{–}20 \text{ m} = \frac{10 \text{ m}}{1.18 \text{ s}} = 8.47 \text{ m/s}$$

Average velocity between 20–30 m

$$20\text{–}30 \text{ m} = \frac{10 \text{ m}}{1.04 \text{ s}} = 9.62 \text{ m/s}$$

Fig. A2.7. Velocity calculations (example 10 m intervals) for 100 m sprint data of university level athlete

1. During first second of motion (5.0 m) the velocity increased rapidly
2. During the next 4.75 seconds the velocity increased to maximum value of about 10 m/s which was achieved at 60 m
3. Maximum velocity (around 10 m/s) maintained for about 1 second to 70 m
4. Velocity decreased steadily from 10 m/s to 9.2 m/s over the last 30 m

'He/she who slows down the least wins the sprint race'

Fig. A2.8. Analysis of velocity data

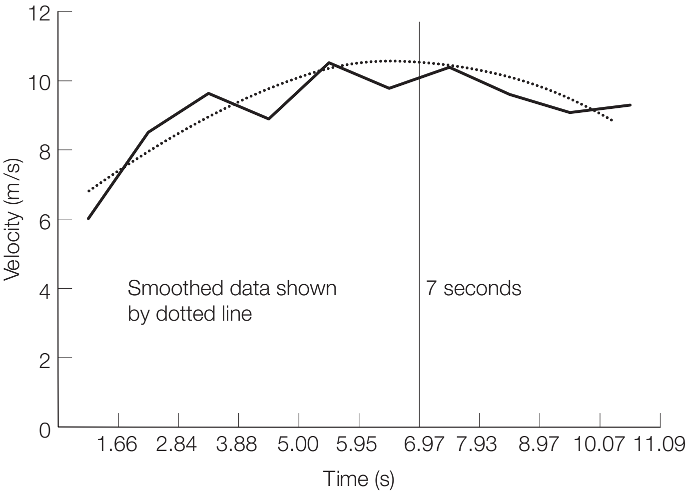

Fig. A2.9. Graphical presentation of velocity data

such knowledge of individual and comparative performances would have important training and performance implications for both the athlete and the coach.

Acceleration

Acceleration is defined as the **change in velocity per unit of time** and it is usually measured in meters per second squared (m/s^2). This means that the velocity of an object will increase/decrease by an amount for every second of its motion. For example, a constant (uniform) acceleration of 2.5 m/s^2 indicates that the body will increase its velocity by 2.5 m/s for every second of its motion (2.5 m/s for 1 second, 5.0 m/s for 2 seconds, 7.5 m/s for 3 seconds and so on). *Figs A2.10*, *A2.11*, and *A2.12* show the calculation and presentation of some acceleration data for the university 100 m sprint performance used in the previous example.

Acceleration is defined as the change in velocity per unit of time
(rate of change of velocity)

$$\text{Acceleration} = \frac{V - U}{t_2 - t_1}$$

U = velocity of the object at time t_1
V = velocity of the object at time t_2
U = initial velocity
V = final velocity

Positive acceleration	Negative acceleration
When the velocity increases over a time period (speeding up)	When the velocity decreases over a time period (slowing down)

Fig. A2.10. Acceleration defined

Analysis of 100 m university sprinter (acceleration)

Acceleration between 0 and 7 seconds

$$a = \frac{10.51 - 0 \text{ m/s}}{7.0 - 0 \text{ s}} = 1.50 \text{ m/s}^2$$

Acceleration between 0 and 11 seconds

$$a = \frac{9.21 - 0 \text{ m/s}}{11.0 - 0 \text{ s}} = 0.83 \text{ m/s}^2$$

Acceleration between 7 and 11 seconds

$$a = \frac{9.21 - 10.51 \text{ m/s}}{11.0 - 7.0 \text{ s}} = -0.33 \text{ m/s}^2$$

Fig. A2.11. Acceleration calculations for selected time intervals (reading values from the graph of velocity vs. time)

From consideration of these gures it is possible to see that the athlete is both accelerating and decelerating throughout the activity. If we now look at the velocity versus time graph (shown in *Fig. A2.9*) we can see that it is possible to read values directly from this graph for speci c time points (i.e., 7 seconds into the race). Between 0 and 7 seconds we can see that there is an average positive acceleration of +1.50 m/s^2 (i.e., indicating the athlete is on average speeding up over this period of time). Between 0 and 11 seconds (almost the whole race) the athlete has an average horizontal acceleration of +0.83 m/s^2. However, more detailed analysis (over smaller time intervals) shows that the athlete is actually decelerating (slowing down) between 7 and 11 seconds in the activity (0.33 m/s^2). This data provides valuable biomechanical information for the athlete and coach that can be used to improve performance. As an alternative to reading speci c time points from the graph we can use the velocity calculations that we have already (i.e., the velocity values for each 10 m displacement). In this context, the following example determines the acceleration between the velocity points of 10.50 and 8.92 m/s (approximately between the 40 and 50 m points).

Acceleration of the athlete between velocity points of 10.50 m/s and 8.52 m/s

Using the formula for acceleration

$$\text{Acceleration (a)} = \frac{v - u}{t_2 - t_1}$$

$$= \frac{10.50 \quad 8.92 \text{ m/s}}{5.95 - 5.00 \text{ = s}}$$

$$= +\mathbf{1.66\ m/s^2}\ \textbf{(average acceleration over this time)}$$

Note: in the context of the graph it can be seen that the values that are plotted are between the points of displacement or time (i.e., indicating an average between two points that is expressed at the mid-point). In addition, considering that velocity is a vector quantity, the positive and negative sign would represent the directional component. A positive velocity value would indicate movement along the 100 m track towards the nish line, whereas a negative value for horizontal velocity would indicate movement back towards the start (which in a 100 m sprint race would not usually happen). However, in terms of acceleration, a positive value would indicate speeding up (accelerating) and a negative value slowing down (decelerating). In this example the velocity and acceleration signs (positive and negative) are independent. However, it is also possible to have a negative acceleration value when the object is speeding up (increasing velocity or accelerating). For example, in the case of acceleration due to the gravity of the earth the acceleration is often expressed as –9.81 m/s^2. This indicates a *downward* (towards the earth) acceleration of 9.81 m/s^2 (i.e., an object will speed up (increase its velocity) as it falls towards the center of the earth (see section on gravity within this text)). However, in the case of acceleration in the horizontal direction (as in the example of our 100 m sprinter) a negative acceleration value would indicate a deceleration (slowing down) of the athlete.

Finally, in terms of biomechanics it is useful to be able to present all of this data in a series of graphs. In order to analyse performance, the coach and the athlete can use the graphs for displacement/time, velocity/time and acceleration/time. *Fig. A2.12* (1–3) presents graphs for the data calculated for the 100 m university level sprinter used in our example. Note that the acceleration data is presented for 10 m intervals between velocity values, as is the data for velocity (i.e., between displacement values). The data is presented both as raw values and smoothed (using a curve of best t) between data points.

From consideration of these graphs, it is possible to see that the velocity data indicates the athlete increases velocity from the start and reaches a peak at around the 60 m point in the race (or at about 7 seconds). At this point the athlete manages to hold this peak velocity for about 1 second to 70 m before it then begins to fall towards 100 m. This is con rmed by the acceleration/time graph, which shows positive (increasing velocity) values up to 60 m. Although it appears that the acceleration/time graph is decreasing during this section, the values are still all positive and are hence indicating acceleration or speeding up. The acceleration/time graph then passes through zero (which at this point would indicate no acceleration), as the athlete would have constant horizontal velocity for this brief 1-second period. Next, the acceleration/time graph becomes

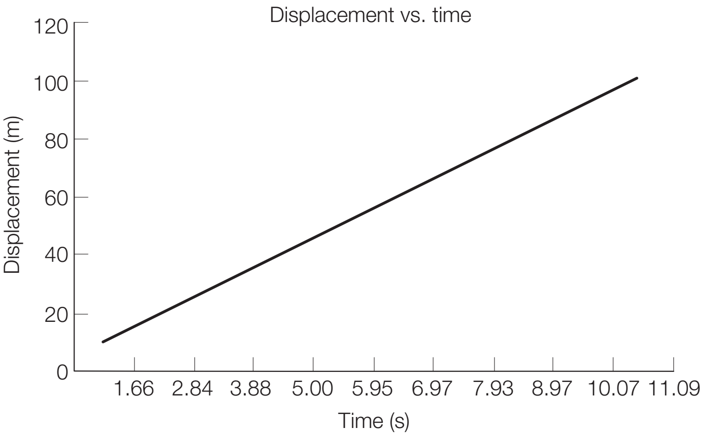

Fig. A2.12(1). Displacement/time, velocity/time, and acceleration/time graphs of data for 100 m university level athlete over 10 m intervals (best fit straight line shown)

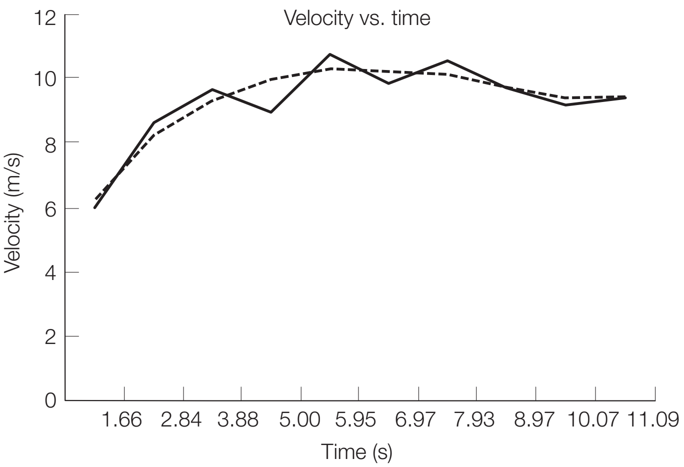

Fig. A2.12(2). Displacement/time, velocity/time, and acceleration/time graphs of data for 100 m university level athlete over 10 m intervals (smoothed data indicated by dotted line)

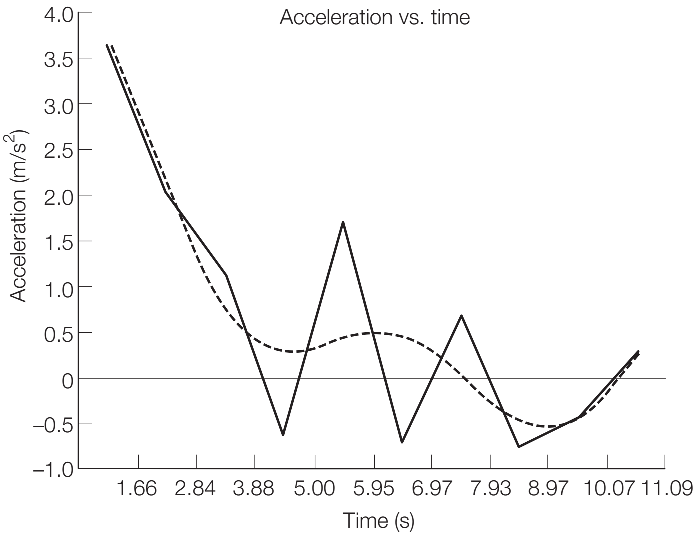

Fig. A2.12(3). Displacement/time, velocity/time, and acceleration/time graphs of data for 100 m university level athlete over 10 m intervals (smoothed data indicated by dotted line)

negative, indicating a deceleration or slowing down (i.e., from about 70 to 100 m). Hence, the statement made by many athletics coaches and biomechanists of *"he/she who slows down the least wins the sprint race"* appears to be true of our 100 m university level sprinter. This characteristic speeding up (increasing horizontal velocity) to a peak at around 60 m, holding this speed for about 1 second and then slowing down as they approach 100 m is typical of many 100 m performances at many different levels (from amateur to Olympic athlete). Hence, it is obvious that such biomechanical analysis may have important implications for both training and performance.

Application

From the following (*Fig. A2.13*) set of data taken from two different world record 1500 m freestyle swimming performances (Kieran Perkins 1994 and Grant Hackett 2001) calculate the average horizontal velocity and acceleration over each 100 m displacement (distance) interval. Also see if you can provide a brief analysis of each swimmer's race. Note: in this context in may be important to qualify that the displacement in a swimming event such as this is technically zero (i.e., the athlete starts, swims 50 m (down the pool length), turns, and then returns to the start again). Hence the term distance and speed are probably more appropriate in this application.

Disp (m)	1994 Perkins	2001 Hackett
100	54.81	54.19
200	1:52.91	1:52.45
300	2:51.48	2:51.29
400	3:50.37	3:50.18
500	4:49.04	4:48.82
600	5:48.51	5:47.45
700	6:47.72	6:45.96
800	7:46.00	7:44.47
900	8:45.28	8:43.05
1000	9:44.94	9:41.78
1100	10:44.63	10:40.56
1200	11:44.50	11:39.51
1300	12:44.70	12:38.51
1400	13:44.44	13:37.89
1500	14:41.66 WR	14:34.56 WR

Fig. A2.13. Two sets of world record 1500 m freestyle swimming data shown over 100 m intervals