Robotica (1996) volume 14, pp 437–443.

The anatomy of a humanoid robot

D.W. Seward, A. Bradshaw and F. Margrave

Department of Engineering, Lancaster University, Lancaster LA1 4YR (UK)

(Received in Final Form: November 23, 1995)

SUMMARY
This paper investigates the feasibility of constructing a humanoid robot using existing technology. Firstly, the adoption of the humanoid form is justified. The structure, strength and power capabilities of a human are analysed in engineering terms, and taken to represent the requirements specification for a humanoid robot. Technological alternatives to the biological components are reviewed and compared to this specification. The feasibility of matching human performance is considered, and it is concluded that the necessary power and energy requirements can be fitted within the mass and volume of the human body.

KEYWORDS: Humanoid robot; Technology; Human performance.

1. INTRODUCTION

The aim of this paper is to investigate the feasibility of using current technology to construct a robot of humanoid form. It is **not** concerned with, say, the analysis of bipedal walking, and the design of a walking machine. It is concerned with the construction of a robot with human physical capabilities, which can then learn (or at least be taught) to walk. This is an important philosophical distinction. In order to have the capability to carry out a wide range of human activities the robot must be of similar size, weight and power to a human. The distribution of weight throughout the body must also be similar if human movements are to be possible. One aim of this paper is to assess the possibility of fitting the required technology into a frame of human size and weight. Clearly the problems of building such a robot are formidable, however it is the authors' contention that it is timely to consider the technological implications.

A recurring dilemma facing this investigation concerns the issue of knowing how closely to remain with the biological analogue. In general the authors have adopted the line that "nature knowns best", and consequently, unless there is good reason to depart from the human model, the human body has been adopted as the target. This is particularly the case with requirements issues, but a more relaxed approach has been adopted when deciding on the most appropriate means of implementation.

Before it is possible to write a specification for a humanoid robot it is necessary to analyse the various functions of the human body in terms that are understandable to the physical scientist or engineer. In this paper it is proposed that only the physical anatomic aspects are considered. The difficult problems of sensing, control, communication and intelligence will be the subject of later papers. Each section starts with the analysis (**Man as Machine**) and then goes on to consider appropriate mechanical analogues (**Machine as Man**). A deliberate attempt has been made to avoid bio-medical Latin jargon.

2. JUSTIFICATION

Current industrial robots bear little resemblance to the traditional humanoid forms widely depicted by science fiction writers. Does this mean that human shaped robots will never be a practical commercial proposition? Certainly it appears that for the performance of specialised tasks in structured environments the optimum configuration of a robot will probably not be anything like the human form. Research into humanoid robots therefore requires some justification.

The lack of adequate sensing systems and intelligence means that, for safety reasons, the current generation of robots must be segregated from humans. This puts severe limitations on the useful fields of application for robot labour. As robots become better equipped to sense their environment, and as they become more intelligent, it will be possible to make them safer and more flexible. The rigid segregation between humans and robots will then be relaxed, and this will open up a vast range of new applications for robots as personal assistants in both the workplace and the home. It is at this point that the humanoid form becomes advantageous. The reasons for this are:

- Such robots will be able to function in the same environment as humans. They will be able to negotiate doorways, stairs and obstructions in the same way that humans can.
- They will be able to use human machines and tools. This is important because it allows humans to intervene and take over a task if it gets beyond the robot's capability (and vice-versa!).
- They will be able to use conventional forms of transport.
- Provided they posses the same physical strength and dexterity as humans, they can, in theory, carry out any human task.
- Such robots would be more socially acceptable when sharing environments with humans.

- They would automatically be imbued with some of the benefits of a hundred million years of evolution (the longest running genetic algorithm).

3. SIZE AND MASS

Clearly humans exist in a wide range of shapes and sizes, and in general, most of them can function adequately in the world. This is comforting as it suggests that functional performance is not too sensitive to variations in physical stature. For the purposes of this study it will be assumed that the target is an adult male of height 1.8 m and mass 75 kg. For the performance of many functions it is also important that the distribution of mass throughout the body is maintained. Figure 1 shows the co-ordinates and masses for the parts of the target human based on data from US Air Force personnel.[1] The figure shows a rear view. The figures on the left skeletal part of the figure show the mass of each component and the z and x coordinates of the centres of gravity. The figures on the right show the co-ordinates of the principal joints. The spine and neck joints have been added by the authors.

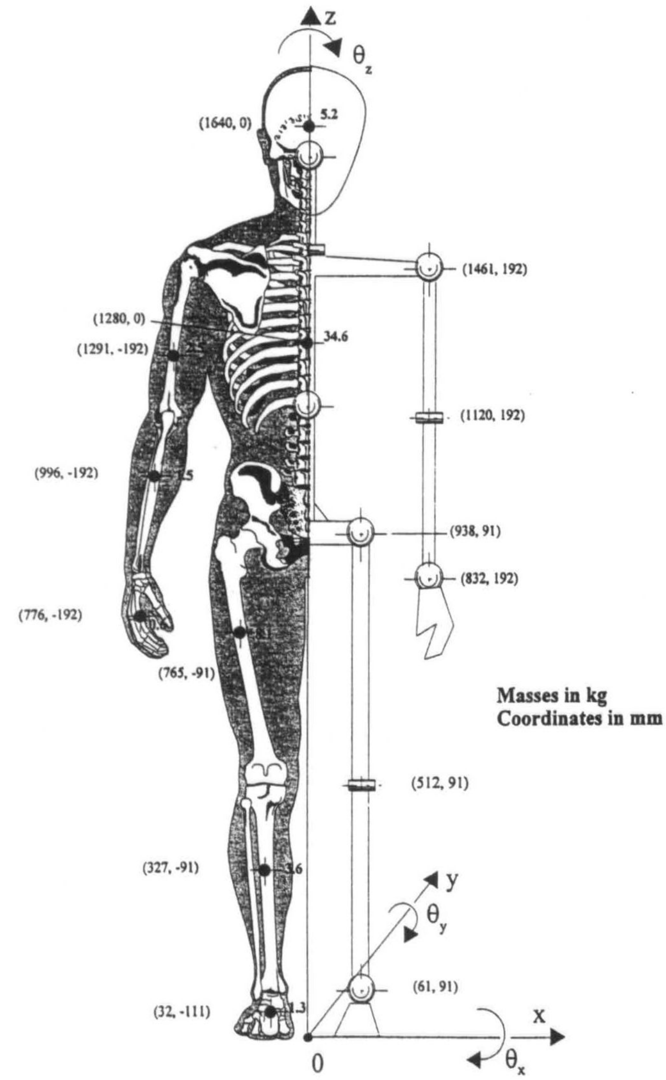

Fig. 1. Mass and centre of gravity of limbs and joint coordinates (Back view).

4. BONES

4.1 Human bones

Bones provide structural strength to the human frame. They provide support to the various organs of the body, and transfer internal and external loads down to the ground. They provide the structure to enable the body to apply forces to the external world, and thus accomplish useful work. It is important that the structural strength of a humanoid robot at least matches that of the human frame.

The principal bones in the limbs are roughly circular in cross-section, with the central portion filled with marrow which is a jelly-like substance with no structural strength. The outer hard bone is a composite material consisting of strong organic fibres in a brittle inorganic matrix. The fibres are in layers and adjacent layers often contain fibres running in different directions. This gives the bone shear and torsional strength. McNeill Alexander[2] reports typical mechanical properties for bone as:

$$\text{Tensile strength, } \sigma = 100\ \text{N/mm}^2$$
$$\text{Modulus of elasticity, } E = 10\,000\ \text{N/mm}^2$$
$$\text{Density} = 2\ \text{Mg/m}^3$$

He also states that, for the human thigh bone, the diameter of the hole down the centre of the hard shaft is about half the outside diameter. Measurements of an actual human skeleton indicate that the outside diameter of the thigh bone is about 36 mm. From this:

$$\text{Second moment of area, } I = \pi/4\ (18^4 - 9^4) = 77\,300\ \text{mm}^4$$
$$\text{Elastic modulus, } Z = 77\,300/18 = 4\,300\ \text{mm}^3$$
$$\text{Max. allowable bending moment} = \sigma Z = 100 \times 4\,300 = 0.43\ \text{kNm}$$

A similar calculation for the upper arm bone, assuming an outside diameter of 24 mm, gives a maximum bending moment of 0.13 kNm

4.2 Robot frame

The most appropriate artificial analogue for bone is reinforced polymer composite. A traditional form of this material is well known "fibreglass", however in recent years there have been significant developments in manufacturing techniques and materials. Hollow tubes can be manufactured very effectively by the pultrusion process, and filament winding techniques can add spiral fibres to provide torsional strength. For extra strength, stiffness and lightness, carbon fibres can be used to replace glass.

Typical mechanical properties for composites with glass fibres and a polyester polymer[3] are:

$$\text{Tensile strength, } \sigma = 250\ \text{N/mm}^2$$
$$\text{Elastic modulus, } E = 130\,000\ \text{N/mm}^2$$
$$\text{Density} = 1.8\ \text{Mg/m}^2$$

It can be seen that these compare favourably with the bone properties given above. If the outside diameter is increased, the tube wall thicknesses can be made much thinner, thus enabling the interior of the tube to be used for housing motors or batteries. For tubes with a 1 mm wall thickness, the required external diameter to match the bending strength of the thigh bone is about 50 mm and to match the strength of the upper arm bone is about 30 mm. This leads to a total skeleton mass of only about 2 kg.

Much superior properties can be obtained using carbon fibres and epoxy polymer:[3]

$$\text{Tensile strength} = 1\,400\ \text{N/mm}^2$$
$$\text{Elastic modulus, } E = 130\,000\ \text{N/mm}^2$$
$$\text{Density} = 1.6\ \text{Mg/m}^2$$

Use of carbon fibres would mean that there could be both increased strength and weight-saving.

5. JOINTS

The bones of the body are connected together at joints which permit various degrees of movement. The simplest types of joint are:

- Hinge joints, such as a finger joint, which can move in only one plane, and hence permit one degree of freedom.
- Double-hinge joints, such as the wrist, which can rotate about two axes, and hence permit two degrees of freedom.
- Ball and socket joints, such as the hip or shoulder, which can rotate about two axes as well as allow some axial rotation – hence three degrees of freedom.

Many movements in the human body are much more complex than the above, and there is little point in trying to define the total number of degrees of freedom in the human body, as this would simply lead to arguments about what is a significant movement. For example how many degrees of freedom should be assumed to occur between the 24 individual vertebrae in the spine? Also some degrees of freedom are not truly independent, such as individual finger joints.

For the purposes of a humanoid robot a considerable simplification can probably be made without significantly affecting its functionality. An example of this simplification concerns the shoulder joint. In humans, as the arm is raised, the initial range of movement is facilitated by the rotation of the ball and socket shoulder joint, but the later stages involve movement of the shoulder blade. In a robot, this movement could be accommodated by simply extending the range of movement of the shoulder joint and keeping the shoulder itself fixed in relation to the spine. This means that the robot would lose some expressive ability, such as shrugging its shoulders. Probably an adequate range of movements can be provided by a combination of single hinge joints and pseudo ball and socket joints. This is shown in Figure 1. The pseudo ball and socket joints would contain individual actuators to control each degree of freedom.

For each degree of freedom it is possible to tabulate the range of angular movement required. This is shown in Table I for the right-hand side of the humanoid shown in Figure 1. The joint positions shown in Figure 1 are taken as the zero for all angles of rotation. These are based on actual measurements of a human, but are, of course subject to considerable variation between individuals. This results in 35 significant degrees of freedom excluding the hands and feet.

Table I. Degrees of freedom for a humanoid robot (excluding hands and feet)

Joint	Degree of freedom	Range of rotation in degrees	
Head	θx	+60	−30
	θy	+70	−70
	θz	+80	−80
Neck	θx	+20	−50
Back	θx	+30	−60
	θy	+55	−55
	θz	+45	−45
Shoulder	θx	+180	−80
	θy	+45	−135
	θz	+30	0
Elbow	θx	0	−155
Wrist	θx	+35	−35
	θy	+60	−70
	θz	+70	−90
Hip	θx	+120	−40
	θy	+40	−50
	θz	+60	−50
Knee	θx	+0	−130
Ankle	θx	+30	−60
	θy	+45	−20
	θz	+20	−60

6. MUSCLES

6.1 Human muscles

Muscles are the effectors that convert chemical energy into mechanical work. They are a form of linear actuator, and are joined to a bone at each end with tendons. They can only operate in tension, and the tensile force is created by muscle contraction. This means that they operate in opposing pairs to give two-way motion, and this makes the control problem easier. The torque generated at a joint is given by the muscle tension multiplied by the lever arm. The value of this torque is highly variable for the following reasons:

- The relationship between the lever arm and the joint angle, θ, is non-linear. Thus the maximum force that can be applied by a limb depends upon the joint angle.
- The maximum muscle tension varies with the muscle length.[4]
- The maximum muscle tension varies with the velocity of contraction.[4]

Owing to the above factors, meaningful figures for muscle power are difficult to come by. Many muscles have merely a 'positioning' role – such as the head and neck muscles, whereas the principal muscles of the limbs are also important for performing actual work. It is therefore necessary to be able to estimate the power of these muscles. Edgerton et al.[4] reports peak values for the human knee of about 180 watts and for the human ankle of about 50 watts. The peak value occurs at about a third of the maximum velocity and half the maximum force. Enoka[5] reports a power of about 200 watts for the elbow muscles, which seems high compared to the above knee value. A more logical way of determining muscle power is therefore required.

Wilkie[6] reported that human muscles can produce up to 500 watts per kilogram. This means that it would be possible to estimate the power of a particular muscle if the mass were known. A problem with this approach is that muscles often run diagonally across the body and are not dedicated to a particular joint. For our purposes it is therefore more meaningful to talk about a **muscle group** that serves a particular degree of freedom.

Another approach is to calculate power from human performance data. Enoka[5] reports that an average human can raise the centre of gravity of their body 324 mm (h_1) above the ground from a static squat jump. This involves initially bending the knees to lower the body by about 200 mm (h_2) and keeping the hands permanently above the head. If we assume that, using leg muscles only, a human applies a constant force to accelerate their body over the distance of 200 mm, we can conclude from simple Newtonian mechanics that:

$$\text{Speed at lift-off, } v = \sqrt{(2gh_1)} = \sqrt{(2 \times 9.81 \times 0.324)} = 2.52\ \text{m/s}$$
$$\text{Acceleration, } a = v^2/2h_2 = 2.52^2/0.4 = 15.9\ \text{m/s}^2$$
$$\text{Force required, } F = (g + a)m = (9.81 + 15.9) \times 75 = 1928\ \text{N}$$
$$\text{Work done, } W = Fh_2 = 1\,928 \times 0.2 = 386\ \text{J}$$
$$\text{Time taken, } t = \sqrt{(2h_2/a)} = \sqrt{(0.4/15.9)} = 0.159\ \text{s}$$
$$\text{Power required, } P = W/t = 386/0.159 = 2\,428\ \text{W}$$

Hubley and Wells[7] report that the knee muscles contribute about 50% of the work in vertical jumping, which would indicate the knee and hip muscles contributing about 600 watts each. This seems a more sensible figure than Edgerton's above.

Also of interest are estimates for maximum angular velocities of rotation and static starting torques. Similar crude calculations can be carried out to obtain them by, for example, considering the velocity of the hand to throw a ball, or the torque required to perform a sit-up. Table II gives approximate values for the principal muscles. The values given represent a best estimate using both published values and the results of simple calculations based on human performance. Two important points are:

- The figures given for power represent **average** values over the whole range of movement, and, as stated above, human limb actuation is non-linear. Muscles may therefore be capable of delivering higher **peak** values.
- No account is taken in the table of static and dynamic stored energy which humans use to supplement muscle work. For example static energy storage occurs when a human crouches in preparation for a squat jump. Provided the thigh muscles are not relaxed they are preloaded in such a way that the stored strain energy assists the jump. A good mechanical example is the 'Anglepoise' desk lamp where potential energy is converted into strain energy in a spring. In order to move the lamp head, a force is required to accelerate the mass of the head but gravity effects are cancelled out by the spring. Dynamic stored energy occurs during activities such as running and jumping. Energy is temporarily stored in the elastic deformation of tendons and muscles. McNeill Alexander[8] estimates that this 'spring-in-the-step' can contribute about 50% of the energy required for dynamic activities with some animals. Clearly a humanoid robot will probably need to exploit energy storage if it is to be competitive.

Table II. Power, speed and torque requirements for limb muscles

Joint	Peak power W	Max velocity rev/min	Starting torque Nm
Shoulder, θx	110	350	70
Elbow, θx	110	150	40
Wrist, θx	30	150	20
Hip, θx	600	300	140
Knee, θx	600	150	160
Ankle, θx	50	150	110

6.2 Robot effectors

There are two candidates for mechanical analogues of muscle. The first is the use of electric motors. Although it has previously been stated that the powers given in Table II are average values, they are in fact only maintained for relatively short periods, and electric motors can be overdriven at say twice their long term rating. However humans use many subtle techniques to maximise muscle efficiency, and past experience has shown that machines invariably need more power to achieve the same functionality. For example, when lifting with the arms, humans will often use their more powerful leg muscles to do extra work. Also humans use their flexibility and compliance to get muscles moving and store elastic strain energy in tendons. It seems prudent therefore to provide motors which are rated to the values given in the table. The question is – can conventional servo-motors provide the performance requirements listed in Table II and at the same time fit within the mass and volume constraints of the humanoid body? Consider the elbow motor, which requires power, speed and torque of 110 W, 150 rev/min and 120 Nm respectively. Trade literature[9] for commercially available servo-motors indicates that a 150 W continuous output motor has a starting torque of 3 Nm with a maximum speed of 6 000 rpm. As a maximum elbow speed of only 150 rev/min is required, a fixed gearing of 40:1 can be used, which increases the starting torque to 120 Nm. It thus exceeds the requirements.

35 degrees of freedom require 35 individual motors. Figure 2 gives an indication of the weight of conventional servo motors of different powers. By assuming that those motors that are used only for positioning purposes are of

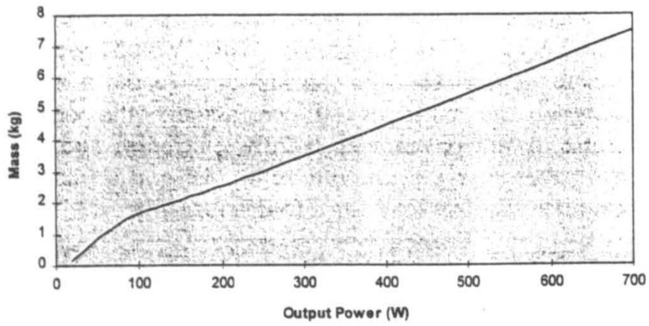

Fig. 2. Mass/power ratio of servo-motors.

say 20 watts average power, the total mass of motors required is 41 kg. Figure 3 demonstrates that, using currently available motors, they will fit inside the humanoid body. However if the motors needed to be fitted with gearboxes, tachometers and encoders this would increase their volume and weight.

There are relatively little known motors based on electrostatic principles with a specific power per unit volume ratio about ten times that of conventional electromagnetic motors.[10,11] Their use would allow substantial reductions in weight, size and energy consumption.

The second candidate for replacing human muscle is artificial muscle. Caldwell et al.,[12] have developed a simple pneumatic system that consists of rubber tubing surrounded by a nylon braided shell. When the muscle is inflated it shortens and produces an axial force. Tests have indicated the potential for very high power/weight ratios such as 1.5 kW/kg at a system pressure of 2 bar. However such actuators can only operate in tension, and so two would be required for each degree of freedom. This results in a total actuator weight of about 8 kg, although each muscle additionally requires a pneumatic control valve. Unless much higher system pressures were used, problems would occur with the volume of pneumatic muscle required to match human muscle. Hydraulic actuators in the form of conventional cylinders may also have a role to play.

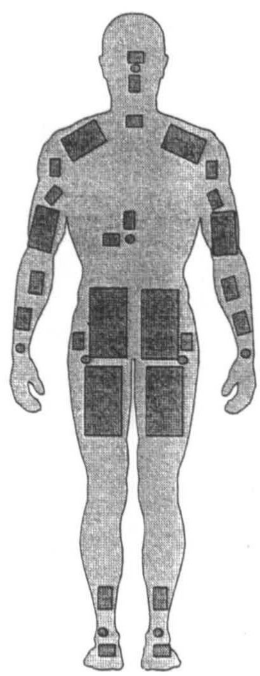

Fig. 3. Principal humanoid motors.

7. TOTAL POWER AND ENERGY REQUIREMENTS

7.1 Human power

The total amount of power that the human body can output is highly dependent upon the duration of the activity. Skeletal muscle fibres are of two types.[13] **Fast twitch** (FT) muscle fibres have their own energy store which is available for immediate use, but has limited capacity. A fuel called phosphocreatine provides a 5 second burst of energy. When this is exhausted carbohydrates in the form of glycogen are used. This is **anaerobic** exercise, and does not make efficient use of energy. The **Slow twitch** (ST) muscle fibres depend upon the circulation of blood to supply oxygen and fuel in the form of glycogen and glucose. This can take about a minute after exercise starts to establish itself. (This explains why athletes warm up before an event). This is **aerobic** exercise and can be sustained for long periods. For very sustained exercise, such as marathron running, the body uses fat as a last reserve of energy. Most muscles contain a mixture of fast and slow fibres.

We have seen above that a jumper can output about 2.5 kW and Enoka[5] repots that a weightlifter can produce a short burst of about 1.8 kW, however sustained power output rapidly falls off to about 375 watts after 10 minutes. Wilkie[6] gives the total energy available for anaerobic activity as 450 watt-minutes (27 kJ) and this is available for use at any time. This represents the area between the two curves shown in Figure 4.

The output required for more sustained exercise can be estimated by considering the power required for a 75 kg human carrying a 25 kg pack to climb a 1 000 m high mountain in 110 minutes.

$$\text{power output} = (100 \times 9.81 \times 1\,000)/(110 \times 60) = 150 \text{ watts}$$

The above assumes that any energy used to raise and

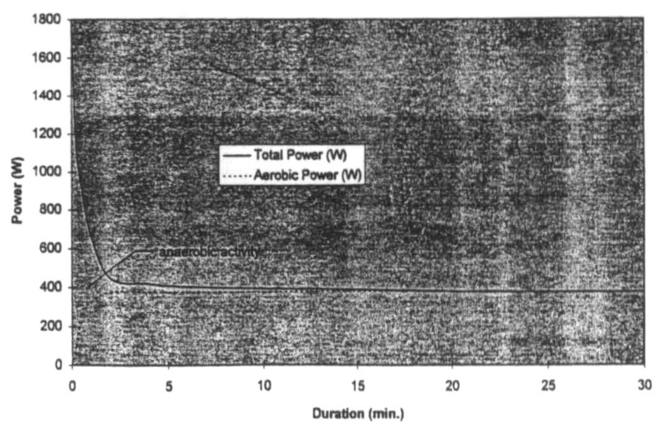

Fig. 4. Human power output over time.

lower the body during each step comes from stored strain energy.

For very long term activity it is possible to estimate power output by considering the conversion of food energy. Wilkie[6] states that the efficiency of muscle for converting chemical energy to mechanical work is a maximum of 25%. Crist et al.[14] indicate that the minimum required energy intake to sustain life is about 7 500 kJ/day. Buskirk et al.[15] gives a required intake for an average lifestyle of 12 350 kJ/day and for very heavy work of 16 700 kJ/day. Therefore if we take the difference between the two extremes and assume the energy is consumed over an eight hour working day, we get:

$$\text{Average power input} = 10^3 \times (16\,700 - 7\,500)/(8 \times 60 \times 60) = 320 \text{ watts}$$

But because muscles are only 25% efficient this only represents a power output of 80 watts.

To summarise, the human has a power source that can provide a steady output of say 375 watts for the first hour followed by 80 to 150 watts for a sustained period together with 27 kJ of energy which can be supplied as required in bursts of up to 2.5 kW. This sums to about 2 500 kJ or 0.75 kWh over a four hour working shift. In an emergency humans also have the useful ability to function at reduced performance for extended periods without refuelling. This graceful degradation can take place over many days, and would be a desirable feature of a humanoid.

7.2 Humanoid power

In the mechanical humanoid, for reasons given above, it would be prudent to double the above figures. It is necessary to decide whether the power would be supplied by a primary energy converter, such as a petrol engine, or simply from energy storage, such as batteries. Work carried out on mobile robots for the SAFFAR Project[16] compared the energy/mass ratios of several power systems, and this is summarised in Figure 5. The work was based on a larger power requirement (58 000 kJ), however the relative values are significant.

7.2.1. Combustion engine plus batteries. If the former strategy were adopted, batteries would also be necessary to provide the extra power for short bursts of energetic activity. Small petrol engine of the order of 375 watts are widely used for hand-held tools, such as chain saws, and weigh only a few kilograms. This would provide adequate power for the background load, and for recharging the batteries. If we assume the engine operates at full power and at 20% efficiency, and that petrol yields energy at the rate of 43.7 kJ/g, it is possible to evaluate the fuel load for a four hour shift:

$$\text{Input energy} = (375/0.2) \times 4 \times 60 \times 60 \times 10^{-3} = 27\,000 \text{ kJ}$$
$$\text{Fuel weight} = 27\,000/43.7 = 620 \text{ g}$$

The energy density for basic lead/acid batteries is 75 kJ/kg, so less than 1 kg of batteries is required, but they must be able to deliver the energy very quickly. It can therefore be concluded that a complete power system consisting of fuel, fuel storage, auxiliary battery and engine should weigh less than 10 kg.

Significant disadvantages of an internal combustion engine include noise, vibration, air pollution and flammability of fuel. These disadvantages may be acceptable in some environments but probably not in the domestic one.

7.2.2. Batteries only. At the other extreme, if the option of all batteries was adopted the total mass of lead/acid batteries would be 2 500/75 = 33.3 kg. The use of nickel-cadmium batteries would reduce this weight by 30% to 23.3 kg, and nickel-metal-hydride batteries by 50% to 17 kg.[17] Sodium sulphur batteries reduce the weight to only 8.1 kg. However sodium sulphur batteries will be discounted at this stage, as they are not yet fully developed and need to be operated at 350°C.[16] A significant advantage of batteries is that they can be spread throughout the body in order to achieve the required mass distribution. Disadvantages include weight and charging time.

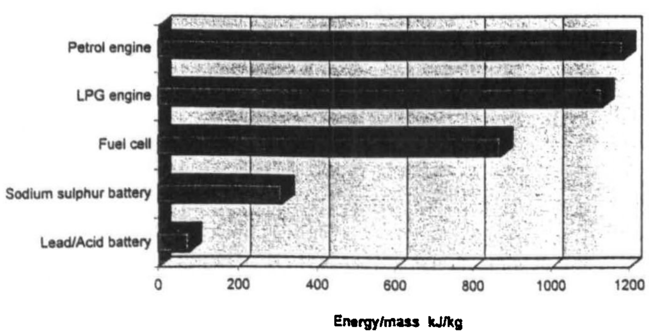

Fig. 5. Energy/mass ratios for various power systems.

8. SKIN

The final element of the human body to be discussed is the skin and other soft tissue that covers the body. This protects the bones (and external objects) from impact damage. The surface is self-healing and self-cleaning. It is the repository for the touch sensory system and it plays a vital role in cooling. Finally, it forms the final reservoir of energy (fat).

It seems unlikely that, in the foreseeable future, robot skin will be as versatile, but it should be touch-sensitive, tough and protective. A closed-cell polyurethane foam would provide an adequate base material, and would weigh less than 2 kg for the entire body. The nature of suitable touch sensors is beyond the scope of this paper.

CONCLUSIONS

The principal properties and capabilites of the human body have been quantified in engineering terms and as a result of this the basic requirements for a humanoid robot have been defined. Existing technology has been reviewed to see if it can match the requirements and in general it seems to be capable of doing so. The components are listed in Table III together with their masses.

Table III. Mass of humanoid components

	kg
Skeleton	2
Motors	41
Energy supply (Ni-Cad)	23.3
Skin	2
Total	68.3

It can be seen from above that the mass of 68.3 kg is less than our target weight of 75 kg, and so, even with existing off-the-shelf technology the humanoid robot looks possible. Clearly the mass of gearboxes, joints, sensors, cables and the control electronics would add significantly to this mass, however current developments in the design of motors and batteries will ensure that the weight target is achievable.

References

1. National Aeronautics and Space Administration, Washington, USA, "Bioastronautics Data Book" **In:** *The Mechanics of Athletics*, 8th ed. (G. Dyson, rev. B.D. Woods and P.R. Travers, eds.) (Hodder and Stoughton, Sevenoaks, UK, 1986) pp. 50–53.
2. R. McNeill Alexander, *Animal mechanics*, (Sidgwick and Jackson, London, 1968).
3. *Design Manual - Engineered Composite Profiles*, (Fibreforce Composites Ltd., Fairoak Lane, Whitehouse, Runcorn, Cheshire, England 1988).
4. V.R. Edgerton, R.R. Roy, R.J. Gregor and S. Rugg, "Morphological Basis of Skeletal Muscle Power Output" **In:** *Human Muscle Power* (ed. N.L. Jones et al.) (McMaster University, Hamilton, Ontario, publ. Human Kinetics Publishers, Inc., Champaign, Illinois, USA, 1986) pp. 43–64.
5. R.M. Enoka, *Neuromechanical Basis of Kinesiology*, (Human Kinetics Books, Champaign, Illinois, USA. 1988).
6. D.R. Wilkier, *Muscle* (Edward Arnold, London, 1976).
7. C.L. Hubley and R.P. Wells, "A work-energy approach to determine individual joint contributions to vertical jump performance" *European J. Appl. Phys.*, **50**, 247–254 (1983).
8. R. McNeill Alexander, "Elastic Energy Stores in running Vertebrates" *Amer. Soc. of Zoologists* **24**, 85–94 (1984).
9. *Hi-Torque range, Permanent Magnet DC Servo Motors* (Evershed and Vignoles Limited, Powerator Division, Acton Lane, London, 1994).
10. F. N-Nagy and G. Joyce, "Solid-state control elements operating on piezo-electric principles" **In:** *Physical Acoustics: Principles and Methods* (ed. W.P. Mason et al.) (Academic Press, New York, 1972) **Vol IX,** pp. 129–166.
11. Anon. "Polymer based motors" *Drives and Controls* (*June*, 1991). *p.* 20.
12. *D.G. Caldwell, A. Razak and M. Goodwin, "Braided Pneumatic Muscle Actuators" 1st IFAC International Workshop, Intelligent Autonomous Vehicles,* University of Southampton, UK (April, 1993) pp. 522–527.
13. E.A. Newsholme, "Application of Metabolic Control to the Problem of Metabolic Limitations in Sprinting, Middle Distance, and Marathon Running" **In:** *Human Muscle Power* (ed. N.L. Jones et al.) (McMaster University, Hamilton, Ontario, publ. Human Kinetics Publishers, Inc., Champaign, Illinois, USA, 1986) pp. 169–182.
14. K. Crist, R.L. Baldwin and J.S. Stern, "Energetics and the Demands for Maintenance **In:** *Human Nutrition* (ed R.B. Alfin-Slater and D. Kritchevsky) (Plenum Press, New York, 1980) pp. 159–182.
15. E.R. Buskirk and J. Mendez, "Energy: Caloric Requirements" **In:** *Human Nutrition* (ed R.B. Alfin-Slater and D. Kritchevsky) (Plenum Press, New York, 1980) pp. 49–50.
16. A. Bradshaw and M. Osborne, "The UK SAFFAR Project: Concept, Function and Control" *Int. Symp. on Advanced Robotic Technology,* Tokyo (March, 1991) pp. 427–434.
17. J. Slater, "The History of Batteries" *Electronics Today International* 49–54 (June, 1993).