Leg Protection for Motorcycles

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1. Introduction

There is a large amount of published evidence which shows that leg injuries are a serious problem in motorcycle accidents, but there has been very little attempt to use this information in developing methods of protecting motorcyclists' legs. There have been only a limited number of controlled impact tests of motorcycles and these have demonstrated that such tests are much more difficult to carry out successfully than controlled impact tests on motor cars.

This paper describes a series of controlled impact tests in which motorcycles with dummy riders ran obliquely into a flat, rigid barrier of the type used in motor car impact tests. These were intended to simulate, in a simple and repeatable way, a common type of accident in which the rider's leg is trapped between the motorcycle and the impacted object. The development of the test technique is described together with its use in the preliminary evaluation of three types of leg protectors.

Grattan et al (1), Whitaker (2) and Pedder et al (3) reported that, though head injuries are responsible for about 75% to 80% of all motorcycle fatalities, the leg is the part of the body which is seriously injured most often. Leg injuries account for just over 60% of all serious motorcycle injuries in Britain. Studies in France (4) also give a figure of just over 60% and studies in Sweden (5) and Germany (6)give an even higher figure of just over 80%. Similar types of behaviour are reported from Japan by Tsuchihashe et al (7), from Nigeria by Shyngle (8) and from Southern California by Newman (9).

Otte et al (6) and Stcherbatcheff (10) found that the most severe leg injuries occur when a motorcycle hits a car obliquely or a car runs into the side of a motorcycle. Whitaker (2) reported that the majority of severe leg injuries were caused by the leg being trapped between the motorcycle and another object, usually a car, during an impact with the side of the motorcycle at various angles. The majority of the injuries were to the lower leg.

Hight et al (11) divided impacts into three categories. In the first the rider stayed on the motorcycle which remained substantially on its original course. This produced mainly knee and femur injuries from direct impact on the knee-cap. In the second the rider was thrown from the motorcycle and blows to the leg occurred from subsequent impacts with the car bonnet or the ground. In the third the motorcycle struck a glancing blow and was deflected from its original course. The rider stayed on the motorcycle and received severe leg injuries. Bourret et al (12) showed that injury depended on the part of the car contacted. The bumper produced tibia and fibula fractures which were reasonably easy to repair. Larger areas of contact, such as the radiator grille, produced several fractures together with serious injury to the soft tissue.

Harms (13) and Grattan & Hobbs (14) showed that it was the legs which were mainly responsible for prolonged stays in hospital and permanent disability. Asche (15) stated that multiple open fractures coupled with bone and tissue infection were responsible for long hospital stays. He found that about 50% of serious leg injuries resulted in permanent disability. Meyrueis et al (16) highlighted oblique impacts as the most frequent cause of leg injuries with the rider sustaining open fractures of the knee cap and femur.

The general conclusion drawn from this information was that the case of the rider's leg being trapped in an oblique impact was worth studying and that injury could occur anywhere along the leg.

2. Test Procedure

Only a few motorcycle crash test programmes have been reported and from these no clearly superior method emerges.

Severy et al (17) used a tow car and cable to pull a dolly along a guide rail. The motorcycle was attached to the dolly at one handlebar and the corresponding front fork and was released nine metres before the impact point. Accuracy of control seems to have been variable. Bothwell (18, 19) and Honda (19) used a car with an outrigger on one side which held the motorcycle until the car was braked and the motorcycle was released to continue on its own. Again accuracy of control seems to have been variable. Bothwell et al (20) also used a trolley accelerated by a linear induction motor. The motorcycle sat just clear of the ground in a channel on the trolley. Just before impact the trolley was stopped by an energy-absorber and the motorcycle continued on its own.

Control seems to have been generally satisfactory. Sacreste et al (21) ran motorcycles down a ramp but give no details. Bartol and Liners (22) and Taneda (23) ran cars into the side of stationary motorcycles and Whitaker (24) used a simulated motorcycle on an impact sled to study rider trajectories in frontal impacts.

It was decided to develop a system using a push car with a framework to hold the motorcycle until it was released. The present system is shown in Fig.1. The motorcycle sits in a channel just clear of the ground and the handlebars are held in the straight ahead position by the frame. On launch the Landrover is braked gently and the motorcycle is released to run forward on its own.

If the motorcycle and rider are carefully adjusted and balanced and the rider's hands are taped lightly on top of the fuel tank, so that the steering is completely free the motorcycle remains upright and runs straight. In order to aim the motorcycle a continuous white line is laid on the approach surface for 250 metres before the impact point. Once the motorcycle is running free the driver of the Landrover has to brake hard to avoid the impact area and the release point has to be chosen to give the best compromise between his safety and the accuracy with which the impact point is hit. It has been found that the release point needs to be about twenty metres from the impact point. Considerable skill is needed by the driver if consistent results are to be obtained.

It was decided, that in the initial tests, stationary, flat, rigid barriers of the type regularly used in motor car impacts would be the most suitable. These may not be very realistic but they are clearly defined and repeatable. Subsequent tests with motorcars as targets and with the motorcycles sliding along the ground are in hand, but this report only discusses tests with flat, rigid barriers. The barrier is 1.23 m high to approximate the height of a car roof. The impact speed was set at 48.3 km/h (30 m/h) in accordance with current legal requirements for motorcar impact tests. About two-thirds of motorcycle leg injuries occur at or below this speed.

At present the most widely used barrier for car impact tests is perpendicular to the vehicle's direction of travel and covers the full width of the car but perpendicular barriers covering only part of the width and angled barriers have been used in research programmes. The full-width perpendicular barrier is used for studying head-on impacts of motorcycles but it makes no contact with the rider's legs. A perpendicular barrier contacting only the leg or the leg protector seemed unrealistically severe so a decision was made to use an angled barrier. This at first was set at 30° to the perpendicular, which is the angle used in motorcar impacts, but the motorcycle behaved substantially as it had with the perpendicular barrier and no leg contact was made. The angle was then increased to 60° to the perpendicular and substantial contact was made between the dummy's leg and the barrier causing significant damage to the leg. Increasing the angle still further made it difficult to hit the barrier so the 60° barrier was chosen for the test series reported here. In accordance with normal practice the steel barrier face is covered with a sheet of 15mm plywood. A typical impact test is shown in Fig. 2.

With this barrier the motorcycle is still moving at 0.5 to 0.75 times its initial velocity after the impact and it has to be brought to rest without further damage to the leg protector or the leg. The barrier is placed just in front of a bed of gravel which was installed for stopping remotely controlled cars which might miss their impact target. The angled barrier is extended towards the gravel by a sheet of 15mm plywood which is curved over at the top so that, after the test impact, the motorcycle is guided into the gravel and encouraged to fall on its undamaged side. A motorcycle after it has been arrested is shown in Fig. 3.

3. Leg Protectors

The following list of design objectives was decided on.

1. Reduction of leg injuries at speeds up to 50 km/h.
2. No increase in leg injuries above 50 km/h or in extreme impacts.
3. No increase in injury to other parts of the body.
4. Reduction of injuries in skidding after falling over.
5. No adverse effect on potential safety devices for frontal impact.

Some relevant information on the performance of leg protectors can be obtained from accident studies and earlier motorcycle crash programmes. Whitaker (2) and Bothwell et al (20) both found that tubular crash bars of the type sometimes fitted do not protect the legs. Bartol & Liners (22) produced a safety motorcycle fitted with a rigid, protective structure on each side. Tests with a car running into the side of a stationary motorcycle showed that leg injuries were prevented but the dummy impacted the car bonnet hard enough to indicate head and chest injuries in people. Taneda (23) in similar tests concluded that up to 35 km/h leg injuries were prevented with no increase in head injuries but above this speed head injuries increased. Other investigators studied head-on impacts where behaviour is different but the rider still needs some form of protection.

Overall the most widely recommended device is a fairing designed to prevent the legs making contact with the impacting object. Such a fairing must be acceptable in appearance and a suitably styled version was made. This is shown in Fig. 4. Two additional simple types of leg protectors were tested and they were designed to approximate to the fairing in location, size and shape.

There appear to be two basic choices available, a hard protector absorbing negligible amounts of energy or an energy absorbing protector. The styled fairings approximated substantially to hard protectors and the two additional types of protector manufactured for these tests were of the energy absorbing type. The theory behind the hard protector is that it deflects the motorcycle away from the impacting object so that the rider can regain control. The theory behind the energy absorbing protector is that some energy is always absorbed on impact and this should be done in a controlled manner.

A tentative assumption was made that the protector should absorb about 20% of the kinetic energy of the motorcycle and rider at 50 km/h. With the medium-weight motorcycles of the present tests this is about 2.5 to 3 kilo-Joules and some static development tests were carried out to provide a device to absorb this amount of energy. This was done successfully but it was found that in the tests of the protector on the motorcycle it absorbed just over 1 kilo-Joule or about 8% of the total kinetic energy. In order to simplify analysis, a simple hollow tetrahedron was chosen which approximated to the shape of the front of the styled fairing. A number of variations were made in mild steel sheet, with and without a filling of weak polyurethane foam and a final version was selected for the barrier impact tests. The device fitted to a motorcycle is shown in Fig.5.

This worked reasonably well but the sharp tip dug into the plywood face of the barrier. Because of this and because a real leg protector could not have such a sharp tip a second version in the form of a semi-cylindrical cone was made. This is shown fitted to a motorcycle in Fig. 6.

4. Assessment of Leg Injury

The motorcycle accident data available at present apply only to motorcycles without leg protectors. Leg injuries can be very severe with multiple fractures and serious damage to soft tissues. There seems to be no published information on the relationships between force and injury for injuries of this magnitude so that leg protectors need to reduce the severity of injury considerably before published criteria of failure can be used. This has led to a two-stage approach to the assessment of likely leg injury in barrier impact tests. The preliminary tests, discussed in this paper, are intended to show that injuries can be reduced to the levels at which published injury criteria apply. In subsequent tests it is hoped to make further improvements using these criteria together with more sophisticated methods of measurement and analysis.

There appear to be two main ways in which loads can be applied to the rider's leg during impact, axial compression of the upper leg produced by an impact on the knee, or transverse impact anywhere along the leg. Axial compression of the upper leg is fairly well understood and it was felt that it would be relatively straightforward to incorporate a suitable energy-absorbing knee pad within the leg protector. No attempt was made to investigate this and attention was concentrated on transverse impacts.

Most of the published information on transverse loading of the leg relates to fracture of the femur or tibia in bending so this was used as a basis for initial assessment. It is not possible to get a consistent relationship between transverse load and maximum bending stress in the bone because this varies with the point of application of the load. In addition it was thought that, in these initial tests electronic instrumentation involving trailing leads on the dummy should be avoided if possible. This made it difficult to record loads or stresses in the dummy's leg. The method decided on was to use a simple deformable leg on the dummy, to estimate the energy absorbed by the leg from its deformation after impact and to relate this to the energy needed to break bones in bending. Yamada (25) estimates the energy needed to fracture the femur in impact bending as about 50J. He also gives load-deflection graphs of the tibia in static bending and, from these, the strain energy at fracture is about 20J. Mather (26) gives the mean energy to break the femur in static bending as 29J and in impact bending as 43J. Snyder (27) quotes unpublished work by Mather in which the fifth percentile value of the energy to break the tibia in impact bending is 35J. It was decided that the leg protectors should prevent fracture and keep soft tissue injuries to a reasonable level and a tentative energy input of not more than 20J was adopted for both the upper and lower leg.

The dummy used in the tests was a fifty-percentile male OPAT. The original legs were replaced by legs made from 12.5 mm thick flat plates. To obtain correct weight distribution the upper leg was made of steel and the lower leg of aluminium. The knee joint was similar in operation to that on the standard dummy leg with an adjustable friction bearing. A machined rod was fitted to the top of the upper leg to fit the existing pelvis joint. A 50mm thick layer of aluminium honeycomb was glued to each side of each leg segment with the axes of the cells perpendicular to the plane of the plate. This honeycomb was chosen from the range commercially available and in static tests 20J energy was absorbed, for instance, by an area of $35 cm^2$ crushed to a depth of 2mm. The load deflection characteristics of honeycomb vary with the direction of loading but, in a series of static tests over a range of angles it was found that behaviour was substantially constant so long as the load was applied within $\pm 45^\circ$ of the axes of the cells and that allowance could be made for other angles of loading. In some of the later tests the legs were covered with chamois leather to indicate skin damage.

The following results were found for 60° barrier impact tests at 50 km/h.

TABLE 1

	Energy Input (J)		
	Upper Leg	Lower Leg	Total
Unmodified motorcycle	135	79	214
Hard Leg Protector	27	40	67
Soft Pyramid Protector	49	54	103
Soft Conical Protector	13	14	27

Values are mean values for from one to three tests.

With the unmodified motorcycle the energy inputs to the leg are from 3 to 7 times the tentative upper limit. All of the leg protectors produce significant reductions in the energy absorbed by the dummy leg which varied from 2.7 to 0.7 times the tentative upper limit of 20J.

5. Overall Behaviour of Motorcycle and Rider

The velocity of the motorcycle just before impact was recorded electronically but all other measurements were made from high-speed film. The positions of specific points on the motorcycle and rider were measured in consecutive frames and from these the displacements of the points or of the straight lines joining them were plotted against the time since the start of the impact. Velocities and accelerations had to be obtained by numerical differentiation of the displacements. This is inherently a rather inaccurate process and a three-point averaging technique was used to reduce random variations in the derived velocities and accelerations. Typical results are shown in Fig.7. The derived velocities appeared to be stable and were used but the derived accelerations were thought to be unreliable and were not used.

TABLE 2

	Motorcycle			Dummy head
	Impact Velocity	Exit Velocity	Mean Angular Velocity	Forward Velocity
Group A				
Unmodified Motorcycle	13.4	9.2	6.7	13.7
Hard Leg Protector	13.5	10.5	4.5	13.3
Group B				
Soft Pyramid Protector	13.7	6.9	2.2	12.9
Soft Conical Protector	13.7	6.7	2.6	12.1

Values are mean values for from one to three tests.

Velocities are in m/sec and angular velocities in rad/sec.

Results are summarised in Table 2 and fall into two fairly distinct groups with the unmodified motorcycle and the one with the hard leg protectors in Group A and the two motorcycles with soft leg protectors in Group B. The positions of the motorcycle longitudinal axis are shown in plan view in Fig.8, at the start of the impact and during the first 100 milliseconds. In Group A the motorcycles have rotated through 22° and are running along the barrier at about half to two-thirds of their initial velocity. In Group B the motorcycles have moved bodily sideways sliding along the barrier, have rotated through about 15° and are travelling at rather less than half their initial velocity.

The attitude of the dummy rider is shown in side view in Fig.9 at the start of the impact and during the first 100 milliseconds. Unfortunately the dummy's torso is not at the same angle at the start of each test being vertical in two examples and inclined forward at up to 30° in the other two. In each of the two groups there were tests in each initial attitude. Despite this there is a consistent variation in the forward velocity of the dummy's head between the two groups. In Group A the head velocity after 100 milliseconds is the same as its initial velocity or slightly higher. In Group B it is about 5% to 10% lower.

The change in the attitude of the leg which was not impacted does not vary consistently between the groups. With the unmodified motorcycle the dummy remains substantially in its initial attitude with only a very slight straightening of the knee and forward rotation of the torso. With both the hard protector and the pyramidical soft protector there is a more pronounced straightening of the knee and considerable forward rotation of the torso.

With the conical soft protector the knee became almost straight because the foot came off its rest but there is not quite so much forward rotation of the torso. The two cases in which there is pronounced forward rotation of the torso are those in which the torso was originally vertical and this may have influenced results but it is difficult to see how it could have influenced the straightening of the knees.

6. Discussion

The preliminary series of tests described in this paper shows that it is possible to launch a motorcycle with a dummy rider into an impact target sufficiently accurately and repeatably for research tests to be run and for the differences in leg protectors to be studied. The test method is not intended for routine testing of the type needed for legislation or quality control.

A flat, rigid impact barrier inclined at 30° to the line of travel of the motorcycle (60° to the perpendicular) gives simple repeatable test conditions for leg protectors. Presumably the results from such a test bear much the same relationship to motorcycle accidents as the results from barrier impact tests on motorcars bear to motor car accidents. It is intended to check this in a series of impact tests into other road vehicles.

Three types of leg protector were tested and all of them reduced appreciably the energy absorbed by the dummy's leg on impact. A tentative upper limit of 20J is suggested for both the upper and lower leg in transverse impact loading. An unprotected leg absorbed three to seven times this amount but protected legs absorbed from less than one to just under three times the tentative upper limit. One of the soft protectors consistently reduced the energy absorbed to less than the tentative upper limit over a series of three tests.

The overall behaviour of the dummy and motorcycle was complex and interpretation is based on examination of films plus numerous measurements. The fitting of hard leg protectors did not adversely affect the overall behaviour of the motorcycle and the dummy rider and the fitting of soft leg protectors improved it slightly, reducing the exit velocity by 30% and the forward head velocity about 5% to 10%. These initial results are encouraging and indicate that useful leg protection on motorcycles is perfectly feasible.

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FIG.1 NEW LAUNCHING FRAME

FIG.2 TYPICAL IMPACT TEST

FIG.3 MOTORCYCLE AND DUMMY ARRESTED IN GRAVEL

FIG.4 HARD LEG PROTECTOR

FIG.5 PYRAMID LEG PROTECTOR

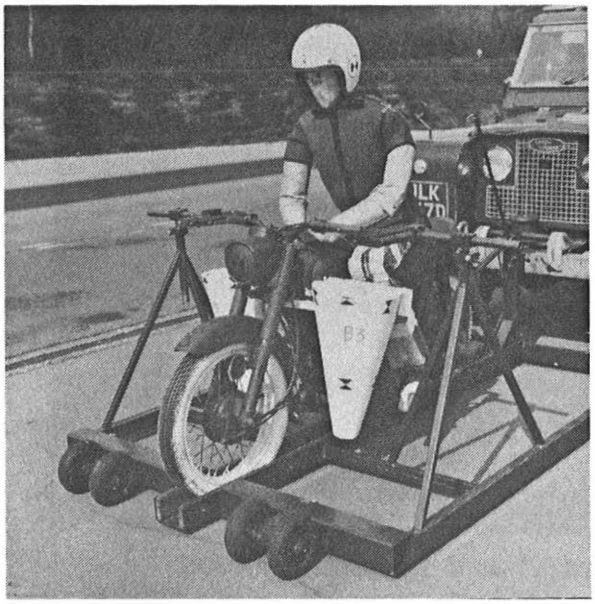

FIG.6 CONE SECTION LEG PROTECTOR

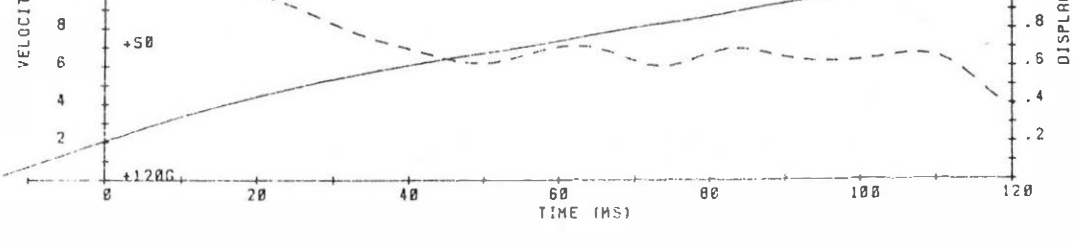

FIG.7 TYPICAL CURVES FROM FILM ANALYSIS

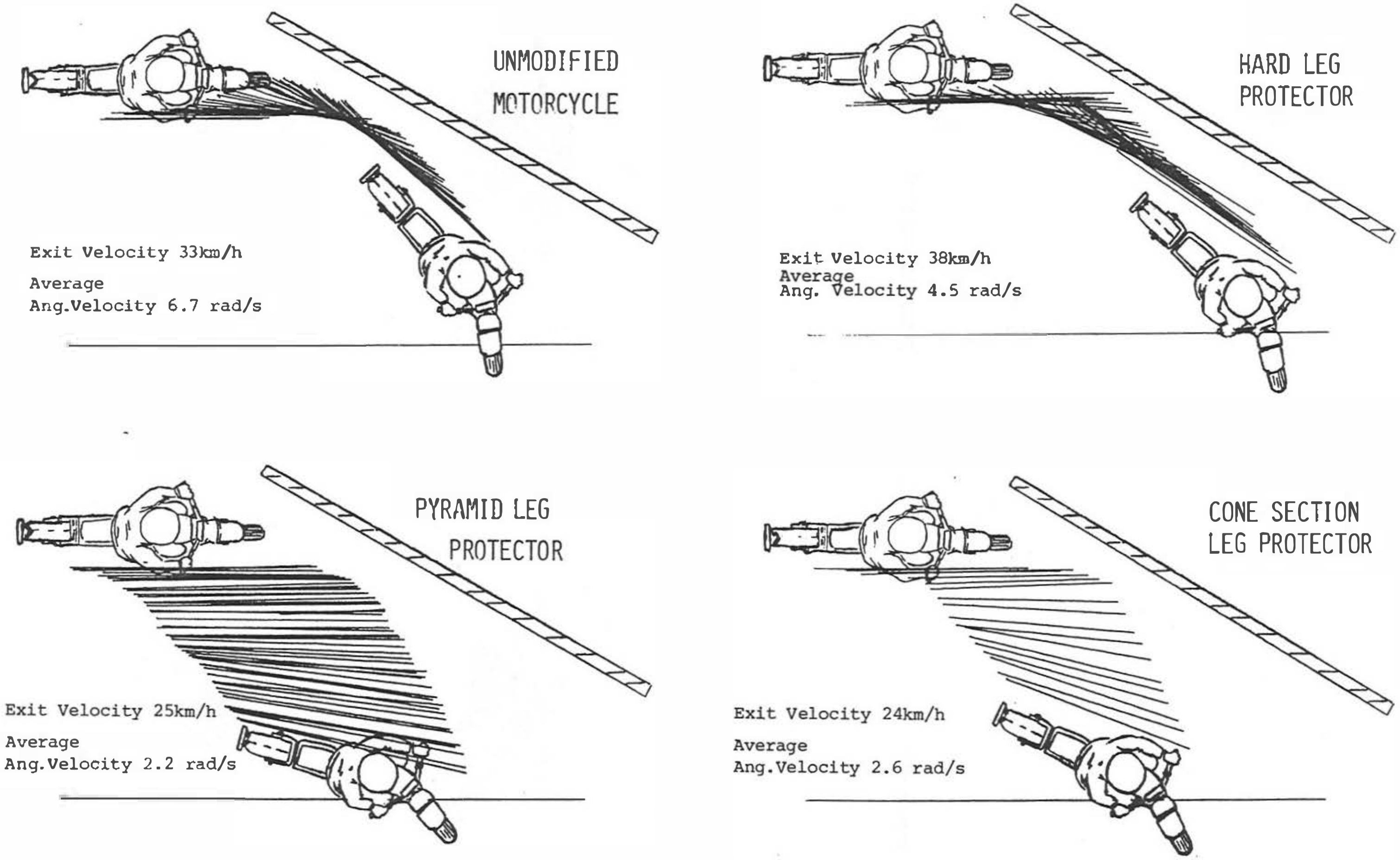

FIG.8 PLAN VIEW OF MOTORCYCLE TRAJECTORY DURING IMPACT (100 - 120 ms)

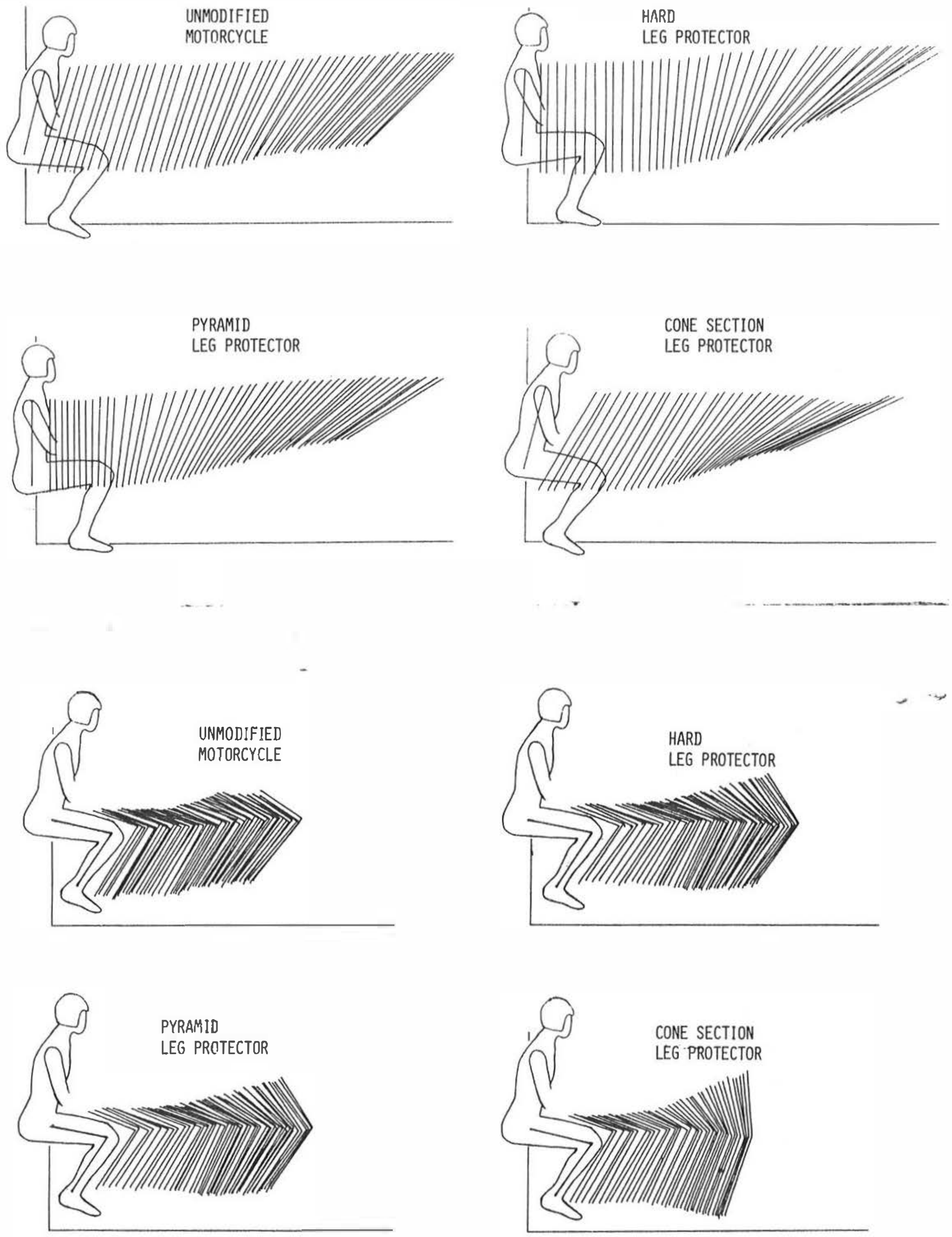

FIG. 9 SIDE VIEW OF TRAJECTORY OF HIP AND SHOULDER (TOP) AND LEG (BOTTOM)