HEAVY PROTECTIVE HELMETS AND NECK INJURIES -

A theoretical and electromyographic study

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ABSTRACT

Heavy protective helmets may cause injuries to the cervical spine and fatigue of the neck muscles. A theoretical analysis was made on the reaction forces in the cervical spine caused in rapid head movements using helmets with different weights and mass distributions. An electromyographic study was made on the fatigue of the neck muscles in ice-hockey players of different ages wearing helmets in static load tests.

Maximum helmet weights are difficult to specify. The inertia forces of heavy helmets may reduce the injury tolerance significantly. In ice-hockey players up to ten years of age, in which the mass of the head is relatively great compared to the body, the helmet mass is recommended to be 0.65 kg or lower. In other categories the helmet mass may be greater but should be as small as possible without reducing the protective effect. The maximum recommended mass depends on the way and time the helmet is used and the protective requirements.

INTRODUCTION

The use of protective helmets has become more important during the last few decades as head protection becomes a necessity for various groups of people. Helmets have been used for a long time by miners, firemen, builders, dockers, soldiers etc. Since 1978 the use of helmets has been compulsory for motorcyclists and moped drivers in Sweden. Since 1963 the use of helmets also has been compulsory for ice-hockey- and bandy-players during competitive matches. In addition the wearing of protective head gear has been recommended during training. Helmets are used in other sports such as downhill skiing, american football, motor-car racing, riding etc. Helmets can be made to specification with the addition of supplementary protection devices as for example the face protection on a welding helmet or the lamp on a miners helmet. In Sweden the face protection is mandatory for ice-hockey players below 18 years of age.

The helmet should protect against penetration and blunt traumas directed against the skull and face. The protective effectiveness against these types of injuries is most obvious for motorcyclists and moped drivers who are involved in traffic accidents (1-5). Studies have shown that helmetless driving almost triple the fatal head injury risks (6). For ice-hockey players the face protection has reduced the risk of injuries to the eyes and teeth considerably (7).

Protection against penetrating forces depends on the toughness and hardness of the helmet surface. Protection against blunt impacts depends on the compliance and thickness of the padding.

Improved protectiveness may lead to increased mass of the helmet (1). This might increase the load on the cervical spine. Such a load increase may accelerate the degenerative process of the cervical spine and may cause fatigue of the neck muscles (8). A heavy helmet might also reduce the ability to concentrate while driving in traffic or performing dangerous work (1). Some serious neck injuries in fatal motorcycle accidents might be caused by too heavy helmets (9).

AIMS OF THE STUDY

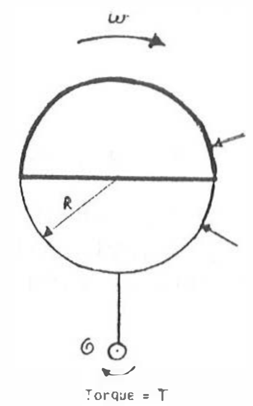
The purpose of this study was to

- theoretically analyse the forces in the cervical spine during static and dynamic loading for individuals wearing helmets of different masses and mass distributions
- investigate the fatigue of the neck muscles during static loading for individuals of different ages
- analyse the effect of wearing helmets of different masses on neck muscle fatigue during static loading.

THEORETICAL STUDY

The forces in the cervical spine and neck muscles depend on the mass of the head and helmet and the distribution of the mass. For a static load the forces are proportional to the mass itself. For a dynamic load the forces depend on the moment of inertia of the head and helmet. The position of the head may alter significantly during a collision and this may cause a violent distorsion of the cervical spine for example as seen in a "whip lash" movement.

A simplified theoretical analysis will illustrate the influence of the mass distribution of the helmet on the reaction forces of the cervical spine during a distorsion (Fig. 1).



Helmet

mass: m

moment of inertia: $I_{ht} = \frac{2}{3} mR^2$

Head

mass: M

moment of inertia: $I_{hd} = \frac{2}{5} MR^2$

Figure 1. Simplified model for analysis of the reaction forces in the cervical spine during a distorsion.

The rotation is determined by

(1) $T = I \cdot \ddot{\omega}$, where

I = the moment of inertia of the mass which rotates around a point 0 in the cervical spine

$\ddot{\omega}$ = the angular acceleration

T = the torque.

The torque and the reaction forces are thus proportional to the moment of inertia of the head and the helmet. The head can be approximated to a sphere and the helmet to half a sphere both with the radius R. The distance between the center of gravity of the helmet and the head is supposed to be 0.25R. This gives the moment of inertia of the helmet equal to $2/3 \cdot mR^3$, where m is the mass of the helmet. The moment of inertia of the head is $2/5 \cdot MR^2$, where M is the mass of the head.

In bending forward, backward or to the side with the centre of rotation at a distance d from the base of the skull the moment of inertia of the helmet is

(2) $I_{ht} = I_{cg} + m(d+R)^2$, where $I_{cg} \approx 0.6\ mR^2$ is the moment of inertia of the helmet about its center of gravity.

The moment of inertia of the head for the same centre of rotation is

(3) $I_{hd} = \frac{2}{5} MR^2 + M(d+R)^2$

If the relative mass of the helmet is equal to p ($m=p \cdot M$) and d=0 (centre of rotation in the upper part of the cervical spine) or d=R (centre of rotation in the lower part of the cervical spine) (3) will give

$I_{ht} = 1.57 \cdot p \cdot I_{hd}$; (d=0) or $I_{ht} = 1.29 \cdot p \cdot I_{hd}$; (d=R)

Thus if the mass of the helmet is 25 per cent of the head mass (p=0.25) the moment of inertia is increased by 30-40 per cent with a helmet.

During rotation in the transverse plane and with the relative mass of helmet equal to p the moment of inertia of the head and helmet is

$$(4) \quad I_{tot} = \frac{2}{5} MR^2 + \frac{2}{3} \cdot p \cdot MR^2 = \frac{6 + 10\,p}{15} \cdot MR^2$$

The relative increase of the moment of inertia in this case is $\frac{10p}{6} = 1.66p$.

For "jet"-helmets, covering the neck and ears, "integral"-helmets, also covering the lower part of the face, and ice-hockey helmets with face protection, the increase of the moment of inertia will be even greater as the helmet is wider in its lower part.

In Table 1 the mass and moment of inertia of some standard ice-hockey- and motorcycle helmets are shown (10). The moment of inertia is calculated for a rotation in the transverse plane. The mass of the head is 3.5 kg, corresponding to 50 kg body weight.

Table 1. Mass and moment of inertia for rotation in the transverse plane for some ice-hockey and motorcycle helmets

Type		Mass		Moment of inertia ($x10^3$)		
		Helmet (kg)	Helmet/Head (%)	Helmet ($kg \cdot m^2$)	Head+Helmet ($kg \cdot m^2$)	Helmet/Head+Helmet (%)
Ice-hockey						
CCM	without face protection	.43	12	4	25	20
	with face protection	.75	21	7	30	30
JOFA	without face protection	.42	12	4	25	20
	with face protection	.67	19	7	30	30
Motorcycle						
"Jet"		.90	26	10	33	43
"Integral"		1.30	37	16	39	70

MUSCULAR FATIGUE STUDY

In the study of muscular fatigue only ice-hockey helmets were used. Myoelectric signals were recorded from the muscles of the neck and shoulder during static load. In four cases the test person was standing with the body bent forward, in 13 cases the individual was sitting with the body bent forward and in 16 cases the person was lying prone. In all cases the face was directed 30-45^{o} down from a vertical plane. Measurements were made without helmets and with helmets with and without face protections as well as extra masses symmetrically fixed outside the helmets. The load varied between zero (no helmet) and 1.94 kg (helmet with a face protection and 1.1 kg extra mass). A minimum pause of ten minutes was made between the tests in each case. The subjective fealing of unsteadiness and fatigue were noted. Records were made from two muscles at the same sime. Bipolar skin electrodes were placed on the cervical part of the trapezius muscle on the right side (muscle 1) and on the suprascapular part of the trapezius on the same side (muscle 2). In three cases intramuscular electrodes were used in the semispinalis capitis muscle on the right side between the spinous process and the skull (muscle 3) and a bipolar skin electrode at the same levelon the contralateral side (muscle 4).

The analysis of the muscular fatigue was made with a computer on line (11). The change of the power spectrum of the myoelectric signals during exercise determines a muscular fatigue index. This index depends on the static load and the anaerobic metabolism of the muscle. The muscular fatigue index has shown to correlate well with the subjective fatigue sensation and discomfort (11).

Results

Thirty-three tests were made with 12 individuals between the ages of 9 and 40 (Table 2). In all cases significant fatigue was noted in at least one of the muscles. In 25 cases significant fatigue was recorded in both muscles. Significant fatigue was noted in all subjects except one. The muscular fatigue index was greater for the younger persons except in the cases where the heaviest helmets were worn. No correlation was found between the muscular fatigue index and the elapsed time before subjective fatigue and unsteadiness was noted.

The cervical part of the trapezius muscle (muscle 1) showed an increased muscular fatigue index for an increased load except for the experiments in which high loads were applied. The suprascapular part of the trapezius muscle (muscle 2) showed a relative constant index. The semispinalis capitis muscle showed small indexes with a minor increment for increased load. The test subjects in these cases were 35 and 40 years old and relatively well-trained. The intramuscular electrode caused discomfort in one of these cases.

Table 2. Muscular fatigue index, time to subjective fatigue sensation and tremor for different helmet masses and ages.

Test subject	Age	Helmet mass	Muscular fatigue index		Elapsed time to	
			Muscle 1	Muscle 2	Subjective fatigue sensation	Tremor
	(years)	(kg)	(min^{-1})	(min^{-1})	(min)	(min)
A	9	0.00	0.028	0.110	1.25	1.25
		0.78	0.030	0.048	1.50	2.00
B	9	0.00	0.095	0.210	2.00	2.50
		0.78	0.068	0.039	2.25	2.25
C	11	0.00	0.007	0.080	7.50	4.00
		0.78	0.069	0.078	7.00	5.00
D	11	0.00	0.002	0.021	7.50	4.00
		0.78	0.005	0.100	7.50	4.00
E	13	0.00	0.000	0.010	3.75	5.00
		0.78	0.100	0.277	3.50	8.00
		0.00	0.000	0.310	0.75	4.25
		0.78	0.085	0.120	0.50	3.00
		1.38	0.230	0.160	1.50	2.75
		1.94	0.020	0.055	2.00	2.50
F	13	0.00	0.017	0.052	4.00	6.00
		0.78	0.008	0.110	4.00	6.00
G	13	0.00	0.002	0.200	1.00	5.00
		0.78	0.005	0.016	1.25	4.50
		1.38	0.048	0.030	0.75	4.75
		1.94	0.050	0.052	0.75	2.25
H	16	0.00	0.023	0.130	3.00	5.00
		1.94	0.078	0.040	1.50	2.75
I	19	1.38	0.036	0.052	4.00	10.00
		0.00	0.014	0.044	1.50	5.00
		0.78	0.024	0.030	1.50	5.00
		1.94	0.027	0.044	1.50	4.50
J	20	1.38	0.055	0.000	2.00	6.00
K	35	0.78	0.009*	0.015**	13.75	15.00
		1.38	0.011*	0.021**	6.75	11.00
L	40	1.38	0.015	0.019	3.50	9.25
		1.38	0.010*	0.000**	0.75	5.00
		0.00	0.028*	0.000**	2.00	5.00
		1.94	0.021*	0.007**	2.50	5.00

* = Muscle 3

** = Muscle 4

COMMENTS

The strength of the tissue of the cervical spine and its muscles is probably adapted to and determined by the mass of the head itself. The extra mass of a helmet might be sufficient to surpass the tolerance limit of the tissue which may result in injury. Degenerative changes of the cervical spine is common. This is noted in 70-80 per cent of people over 50 years of age (12) even without the previous use of helmets. The cervical spine has a significant range of motion (13). An increased load on the cervical spine thus seems to be unacceptable. It should be important to avoid wearing heavy helmets in extreme deflections of the cervical spine for long periods of time as well as during rapid head movements. This might be even more important for young individuals.

The motorcycle helmets were about twice as heavy as the ice-hockey helmets in this study. The mass of the head is about 7 per cent of the body mass (8). In young children the relative mass of the head is somewhat greater. The mass of the helmet increases the static load on the cervical spine by 12-37 per cent (Table 1). The dynamic load increment is greater because of the moment of inertia of the helmet. Extension, flexion and bending increase the dynamic load by 30-40 per cent if the mass of the helmet is 25 per cent of the mass of the head. Rotation in the transverse plane increased the load by 20-70 per cent. Presumably the risk of injuries to the cervical spine and the neck muscles during rapid movements of the head as in collisions and falls will increase with the same amount.

The muscular fatigue study was made using varying techniques on individuals of different ages. The youngest ones tried all mean to change the body position to avoid fatigue and were not able to maintain a fixed position of the body during the whole test sequence. This might influence the variation of the results. Subjective fatigue was noted after one minute in three test persons where no helmets were worn. Thus static load seems to be of great importance for the development of muscular fatigue when the head is bent forward from an erect position. In some tests a reduced muscular fatigue index was recorded for the greatest loads. This result might be due to recruitment of neighbouring muscles.

An increased muscular fatigue index was noted for the cervical part of the trapezius muscle (muscle 1) in seven of ten tests between 0 and 1.34 kg helmet mass.

A linear regression model was calculated defined by the equation

(5) $\beta = 0.048 + 0.029 \cdot (\text{helmet mass (kg)}) - 0.0021 \cdot (\text{age (years)})$,

the normalized standard deviation being 27 per cent.

The time passed before muscular fatigue is noted is given by the "time to fatigue" value (14):

(6) $T_f = \beta^{-2/3}$

Equation (5) determines the T_f-values for different ages and helmet mass (Fig. 2). This indicates that the "time to fatigue" is theoretically eight minutes for a 15-years old person if the helmet mass is 1 kg.

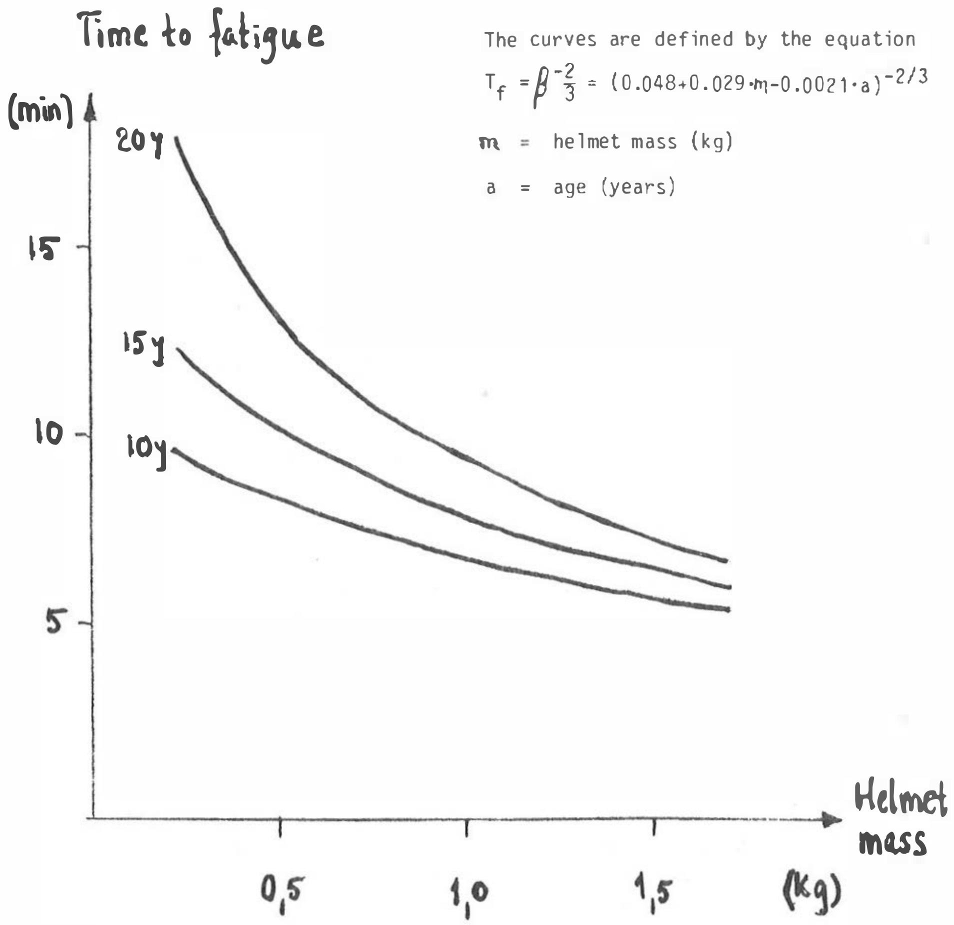


Figure 2. Theoretically predicted time to fatigue as a function of helmet mass for different ages (according to the fitting curve).

A 0.65 kg maximum helmet weight (including the face protection) is prescribed today for ice-hockey- and bandy-players. Maximum weight recommendations also exist for riding helmets but not for other types of helmets. Motorcycle helmets have a great mass. The mass of the padding of the motorcycle helmets does not contribute very much to the total mass. Its density is 50 kg/m^3 (1). However, this padding does increase the distance between the head and the protective shell. The mass of the shell 0.6-0.9 kg (1) cannot be neglected, especially in dynamic loading because of the great moment of inertia of the shell.

The theoretical analysis in this study does not indicate a maximum tolerable helmet mass. The muscular fatigue study gives some indications that a 1 kg helmet might be too heavy for a 15-years old person. However a more extensive study has to be made to assess the tolerance limit of the cervical spine. Considering the moment of inertia and the fact that the mass of the head itself might cause fatigue in certain positions, it seems necessary that the helmet mass should be as small as possible, provided that the protective effect can be guaranteed.

SUMMARY AND CONCLUSIONS

A heavy helmet and the additional mass of extra protection devices on helmets results in an increased load on the cervical spine. However, considering the overall protective effect of helmets, this should not lead to a reduced use of helmets. Helmets should be designed in such a way that the disadvantages of the extra mass is minimized. Prolonged static load of the cervical spine may cause muscular fatigue and difficulties to concentrate while driving in traffic and performing hazardous work. An increased risk of degenerative changes and chronic pain has not been proved but seems likely.

Dynamic load may cause reaction forces in the cervical spine which are twice as high as those recorded in static load. Fatal neck injuries have been noted in motorcycle accidents in which heavy helmets may have contributed to the injuries. The risk of degenerative injuries following repeated and violent movements is increased by the same amount. The risk is greater in collisions and contact sports when the person is exhausted and unable to coordinate the muscles in protection of the cervical spine.

This study shows that muscular fatigue occurs in a short time when the neck is in a position of forward flexion. A helmet mass equal to 0.5-1.5 kg increases the fatigue in the cervical part of the trapezius. The fatigue is more obvious in young people and occurs earlier if the helmet is heavier. Muscle fatigue was noted within a couple of minutes if the helmet mass was 1 kg.

A maximum helmet mass cannot be assessed from this study. The mass of some motorcycle helmets is near 1.5 kg today. This may be acceptable for an adult if considering only static load during short periods. However, a smaller helmet mass is preferable for children and adolescents and for adults if the risk of disturbed concentration, degenerative changes, and acute injuries during violent dynamic loads is considered.

A 0.65 kg maximum weight for ice-hockey helmets has been recommended by the Swedish, Canadian and American Ice-hockey Federations. This limit seems reasonable for adult players. A lower limit (0.5 kg) has been discussed for younger junior ice-hockey players in North America. Our study suggests that this limit should be recommended in Sweden for younger junior players too. Until further studies have been made similar recommendations should be given for other types of protective helmets too.

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