also shown in fig. 1. Nevertheless the two very different types of results are still in reasonable agreement. No attempt has been made to obtain extrapolated zero shear viscosity data using the corrected capillary viscometer data, for *Sabia*'s work was carried out on uncorrected results.

Acknowledgements

The author is indebted to Dr. *G. Downs* who carried out the capillary viscometer experiments and to British Hydrocarbon Chemicals Ltd. for kindly allowing their publication. He also wishes to thank Dr. *K. Lawrence* and the Distillers Company Ltd. for their assistance and supply of samples, and Professor *Weissenberg* for discussion.

Summary

Three polyethylene melts were measured on a *Weissenberg* Rheogoniometer and a capillary rheometer. A method of extrapolating zero shear values of viscosity from the capillary data, described by *Sabia*, is used and the results compared with those measured by the Rheogoniometer.

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A Rheological Measurement of Three Synovial Fluids

By R. G. King

With 7 figures and 5 tables

(Received September 20, 1965)

The Apparatus

The *Weissenberg* Rheogoniometer enables the complete stress distribution in a liquid to be measured in rotation or oscillation or a combination of the two.

Measurement of Viscosity

A cone and plate in rotation were used for these measurements.

The total torque on a plate from a liquid under shear can be expressed by:

$$\text{Total torque} = \frac{4\,\pi^2\,\eta\,r^3}{3\,t\tan\alpha},$$

where

r = radius of cone
η = viscosity of fluid
t = time for one revolution of the plate
α = cone angle

Using Formulae

Rate of shear ($\dot{S}$)

$$\dot{S} = \frac{2\,\pi}{t\tan\alpha}$$

Tangential stress (P_{21})

$$P_{21} = \frac{\Delta T\,k_T}{2/3\,\pi\,r^3}\ \text{dynes/cm}^2$$

Table 1. Knee Joint

Rate of Shear	Tangential Stress		Viscosity (apparent)
sec^{-1}	dynes/cm²		poise
	Maximum Value	Equilibrium Value	Equilibrium Value
0.0138	2.3	2.3	166.6
0.0276	4.6	4.6	166.6
0.0436	6.8	6.8	156.0
0.0872	10.4	8.8	100.7
0.138	12.8	10.4	75.4
0.276	16.8	13.2	47.8
0.434	21.0	15.0	34.57
0.872	29.0	20.0	22.94
1.38	35.0	22.0	15.94
2.85	48.1	27.4	9.62
4.5	57.0	31.0	6.66
9.0	74.0	38.5	4.27
14.2	92.5	44.4	3.12
28.5	120.0	55.0	1.86
45.0	150.0	66.0	1.47
90.0	218.0	77.7	0.86
142.0	270.0	85.0	0.60
285.0	380.0	102	0.36
450.0	460.0	117.0	0.26
900.0	700.0	144.0	0.16
1420.0	900.0	156.0	0.11
2850	1300.0	200.0	0.07
4500	1700.0	225.0	0.05
9000	2500.0	270.0	0.03

where

ΔT = movement of torsion head in thousandths of an inch

k_T = torsion bar constant in dynes · cm/thousandths of an inch

Viscosity (η_{app})

$$\eta_{app} = \frac{P_{21}}{\dot{S}} \text{ dynes/sec/cm}^2 .$$

Knee Joint Samples

Table 1 gives the values of P_{21} and η_{app} obtained for this sample.

At low shear rates the sample was *Newtonian*, and a viscosity at η_0 of 166.6 poise was measured.

Above a shear rate of 5×10^{-2} sec^{-1} the sample became markedly non-newtonian and exhibited a high peak stress in response to the velocity of the shear application, falling to an equilibrium value. The ratio of peak to equilibrium value increased as shear rate was increased. A typical recorder trace from the newtonian and non-newtonian region is shown in figs. 1 and 2. An ultra-violet recorder was used to determine the actual peak values of stress. It will be seen in fig. 2 that the values of stress falls immediately after the peak, and then increases to an equilibrium value. This drop in viscosity is caused by the extreme shear sensitivity of the sample responding to an increase in the natural frequency amplitude of the torsion measuring system, caused by the initial movement of the instruments mechanism and the acceleration of the sample. After 20 seconds or so this increase in natural frequency dies away and the viscosity recovers to a steady value. When the sample was given a short rest period of about 30 seconds, the peak and equilibrium values could be readily repeated at a given rate of shear. If the shear was applied earlier than the rest period mentioned, the peak value was much reduced, although the equilibrium value remained unchanged. Figs. 3 and 4 contain plots of P_{21} and η_{app} for this sample.

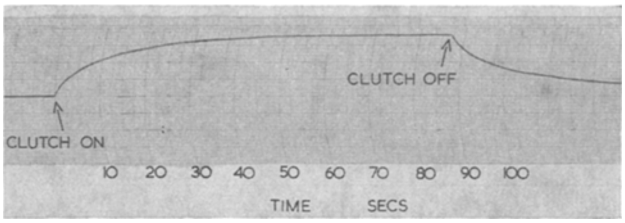

Fig. 1. Vide text

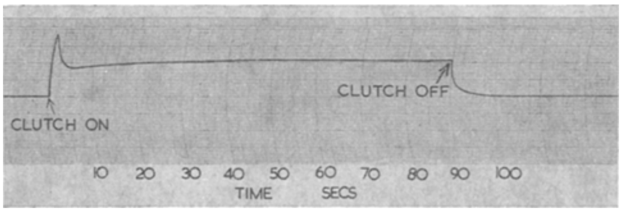

Fig. 2. Vide text

Ankle Joint Fluid (Animal 'A')

This sample was newtonian at low rates of shear, and a viscosity at η_0 of 1.0 poise was measured. The sample became non-newtonian at higher rates of shear, although the peak and equilibrium characteristics encountered with the knee joint sample were not repeated.

Table 2 gives the values of tangential stress (P_{21}) and viscosity and figs. 3 and 4 are plots of these values.

Table 2. Ankle Joint 'A'

Rate of Shear sec^{-1}	Tangential Stress (P_{21}) dynes/cm^2	Viscosity (Apparent) poise
0,045	0,045	1.0
0.09	0.09	1.0
0.1422	0.14	0.99
0.285	0.28	0.98
0.45	0.43	0.95
0.9	0.77	0.85
1.422	1.1	0.77
2.85	1.7	0.60
4.5	2.25	0.50
9.0	3.33	0.37
14.22	4.0	0.29
28.5	6.0	0.21
45.0	7.2	0.16
90.0	10.8	0.12
142.0	13.5	0.095
284.0	18.74	0.066
450.0	24.3	0.054
900.0	34.0	0.038
1422.0	43.0	0.030
2850	62.7	0.022
4500	76.5	0.017
9000	108.0	0.012

Ankle Joint Fluid (Animal 'B')

A sample of fluid from the ankle joint of another animal was then tested. At low shear rates newtonian behaviour was again exhibited. The value of η_0 being 1.1 poise.

At higher shear rates the material became non-newtonian and exhibited peak and equilibrium values in a similar manner to the knee joint sample, although the peak value was only 30% above the equilibrium value on average.

Table 3 gives the values of these measurements, and figs. 3 and 4 are plots of these values.

Table 3. Ankle Joint 'B'

Rate of Shear	Tangential Stress (P_{21})	Viscosity (Apparent)
$\sec^{-1}$	dynes/cm²	poise
0.045	0.05	1.1
0.09	0.1	1.1
0.1422	0.16	1.1
0.285	0.3	1.08
0.45	0.46	1.02
0.9	0.85	0.95
1.42	1.2	0.85
2.85	1.7	0.68
4.5	2.6	0.58
9.0	4.0	0.44
14.22	5.0	0.35
28.5	7.4	0.26
45.0	9.5	0.21
90.0	13.5	0.15
142.0	17.0	0.12
285.0	24.2	0.085
450.0	30.6	0.068
900.0	44.1	0.049
1422.0	55.4	0.039
2850	79.8	0.028
4500	117.0	0.026
9000	153.0	0.017

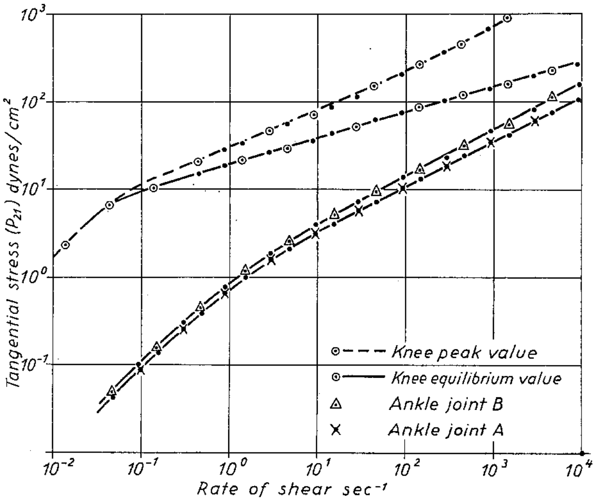

Fig. 3. Vide text

Determination of Normal Stress

Normal Stress $(P_{11} - P_{22})$

$$P_{11} - P_{22} = \frac{2\,\Delta n\, k_N}{\pi r^2} \text{ dynes/cm}^2$$

where

Δn = deflection of normal force spring in thousandths of an inch.

k_N = normal force spring constant in dynes/thousandths of an inch.

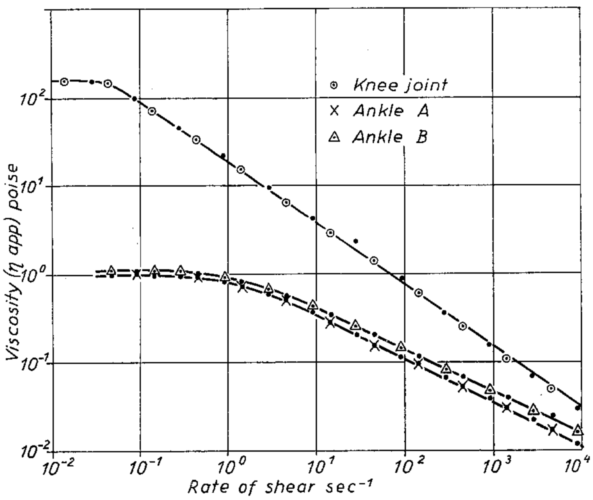

Fig. 4. Vide text

Normal Stress Measurements

Knee joint fluids.

As in the tangential stress measurements the characteristic high peak and equilibrium values were again displayed. Table 4 lists these values together with a calculated shear

Table 4. Knee Joint

Rate of Shear	Normal Stress $(P_{11} - P_{22})$ dynes/cm²		Shear Elasticity (γ) dynes/cm²	Recoverable Shear Strain (γ_e)
$\sec^{-1}$	Peak values	Equilibrium values	From Equilibrium values	From Equilibrium values
90.0	420	270	22.4	3.46
142.0	1020	510	14.2	6.0
285.0	3630	1020	7.6	11.6
450.0	9180	1530	6.4	10.0
900.0	15000	4080	5.1	28 33
1420.0	31000	6120	3.9	39.23
2850.0	68000	10200	3.9	51.0
4500.0	106000	18000	2.8	80.0
9000.0	200000	35000	2.1	129.63

Table 5. Ankle Joint 'B'

Rate of Shear	Normal Stress	Shear Elasticity (γ)	Recoverable Shear (γ_e)
$\sec^{-1}$	Equilibrium value	dynes/cm²	
142.	100	2.9	5.88
285.	240	2.4	10.0
450.	410	2.3	13.4
900.	820	2.3	18.64
1422	1300	2.4	23.64
2850.	2400	2.7	30.0
4500.	3000	3.4	33.00
9000.	6100	3.9	39.87

elasticity (γ) and recoverable shear strain (γ_e), using equilibrium values of stress. Figs. 5, 6 and 7 show plots of these values.

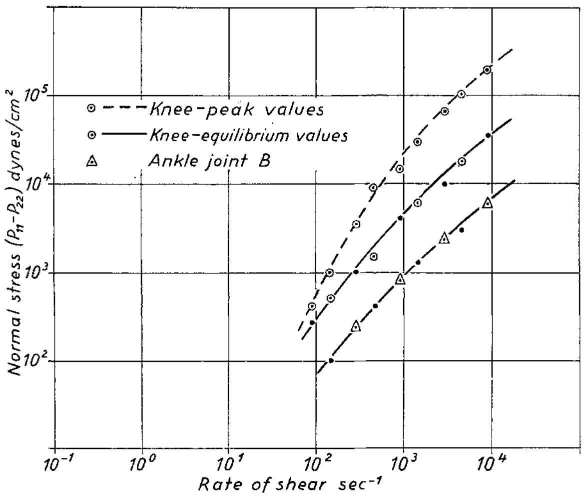

Fig. 5. Vide text

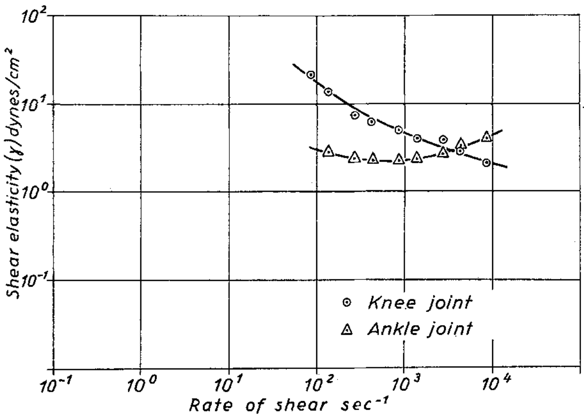

Fig. 6. Vide text

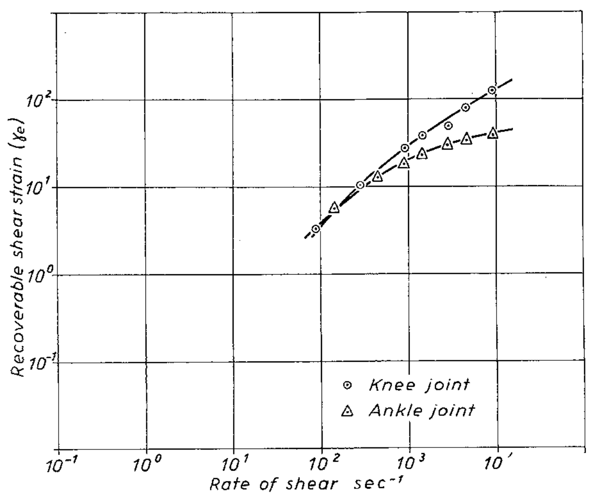

Fig. 7. Vide text

Ankle Joint (Animal 'A')

No normal stress was measurable over the rates of shear used.

Ankle Joint (Animal 'B')

A table of normal stress (equilibrium values) measured in this sample is given in table 5. Figs. 5, 6 and 7 are plots of normal stress, recoverable shear strain (γ_e) and shear elasticity (γ) based on equilibrium values of tangential and normal stress.

Conclusions

The information given in this report was obtained during one day or so of testing, as only limited amount of sample was available. Given more sample, it would have been of interest to explore the responce of the fluids to oscillatory shear etc., and to other tests, but this report was thought to be worth writing in the hope that it may stimulate the interest in this type of measurement, of workers more actively engaged in the field of Biorheology.

The Samples

The samples were obtained from freshly killed bullocks. One sample from the knee joint and the other two were from the ankle joints of separate animals.

Acknowledgements

The author wishes to express thanks to Professor *Davies* and Dr. *Palfrey* of St. Thomas' Hospital, London, where similar work described here is now continuing, for the supply of samples.

Summary

Using a *Weissenberg* Rheogoniometer, three samples of bovine synovial fluid were tested at room temperature (60 °F) at shear rates from 1.0×10^{-2} to 9.0×10^3 sec^{-1}.

There is no apparent explanation for the absence (or small value outside the instruments' range) of normal stress in ankle fluid 'A'. No information was available as to the rearing environment of the animals.

It is clear, however, that synoval fluid can exhibit a high elastic component. The shear rate to which the fluid is subjected during the normal action of the joint is probably quite as high as the maximum value used in these tests.

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